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TEXT-BOOK OF GEOLOGY

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&c., &c.

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PREFACE TO THE THIRD EDITION

THE present edition of this Text-book has been entirely revised, and in some portions recast or rewritten, so as to bring it abreast of the continuous advance of Geological Science. The additions made to the text, which extend to every branch of the subject, increase the volume by about 150 pages. Care has been taken to preserve a characteristic feature of former editions by inserting references to the more important memoirs and papers, where the student will find fuller information than can be given in a Text-book.

While the book was passing through the press I received from my friend Prof. Zirkel the first volume of the new edition of his great text-book of Petrography, but too late to avail myself of its assistance. I can only now recommend it as an indispensable part of the outfit of every serious student of the petrographical section of Geology.

In the revision of the stratigraphical portion of this work I have been assisted with suggestions and information by my colleagues, Mr. Topley, Mr. H. B. Woodward, Mr. E. T. Newton, and Mr. C. Reid, to whom my best thanks are due.

MUSEUM, JERMYN STREET,
1st *August* 1893.

FROM THE PREFACE TO THE FIRST EDITION

THE method of treatment adopted in this Text-book is one which, while conducting the class of Geology in the University of Edinburgh, I have found to afford the student a good grasp of the general principles of the science, and at the same time a familiarity with and interest in details of which he is enabled to see the bearing in the general system of knowledge. A portion of the volume appeared in the autumn of 1879 as the article "Geology" in the *Encyclopædia Britannica.* My leisure since that date has been chiefly devoted to expanding those sections of the treatise which could not be adequately developed in the pages of a general work of reference.

While the book will not, I hope, repel the general reader who cares to know somewhat in detail the facts and principles of one of the most fascinating branches of natural history, it is intended primarily for students, and is therefore adapted specially for their use. The digest given of each subject will be found to be accompanied by references to memoirs where a fuller statement may be sought. It has long been a charge against the geologists of Great Britain that, like their countrymen in general, they are apt to be somewhat insular in their conceptions, even in regard to their own branch of science. Of course, specialists who have devoted themselves to the investigation of certain geological formations or of a certain group of fossil animals, have made themselves familiar with what has been written upon their subject in other countries. But I am afraid there is still not a little truth in the charge, that the general body of geologists here is but vaguely acquainted with geological types and illustrations other than such as have been drawn from the area of the British Isles. More particularly is the accusation true in regard to American geology. Comparatively few of us have any adequate conception of the simplicity and grandeur of the examples by which the principles of the science have been enforced on the other side of the Atlantic.

Fully sensible of this natural tendency, I have tried to keep it in constant view as a danger to be avoided as far as the conditions of my task would allow. In a text-book designed for use in Britain, the illustrations must obviously be in the first place British. A truth can be enforced much more vividly by an example culled from familiar ground than by one taken from a distance. But I have striven to widen the vision of the student by indicating to him that while the general principles of the science remain uniform, they receive sometimes a clearer, sometimes a somewhat different, light from the rocks of other countries than our own. If from these references he is induced to turn to the labours of our fellow-workers on the Continent, and to share my respect and admiration for them, a large part of my design will have been accomplished. If, further, he is led to study with interest the work of our brethren across the Atlantic, and to join in my hearty regard for it and for them, another important section of my task will have been fulfilled. And if in perusing these pages he should find in them any stimulus to explore nature for himself, to wander with the enthusiasm of a true geologist over the length and breadth of his own country, and, where opportunity offers, to extend his experience and widen his sympathies by exploring the rocks of other lands, the remaining and chief part of my aim would be attained.

The illustrations of Fossils in Book VI. have been chiefly drawn by Mr. George Sharman; a few by Mr. B. N. Peach, and one or two by Dr. R. H. Traquair, F.R.S., to all of whom my best thanks are due. The publishers having become possessed of the wood-blocks of Sir Henry de la Beche's 'Geological Observer,' I gladly made use of them as far as they could be employed in Books III. and IV. Sir Henry's sketches were always both clear and artistic, and I hope that students will not be sorry to see some of them revived. They are indicated by the letter (*B*). The engravings of the microscopic structure of rocks are from my own drawings, and I have also availed myself of materials from my sketch-books. The frontispiece is a reduction of a drawing by Mr. W. H. Holmes, whose pictures of the scenery in the Far West of the United States are by far the most remarkable examples yet attained of the union of artistic effectiveness with almost diagrammatic geological distinctness and accuracy. Captain Dutton, of the Geological Survey of the United States, furnished me with this drawing, and also requested Mr. Holmes to make for me the cañon-sections given in Book VII. To both of these kind friends I desire to acknowledge my indebtedness.

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INTRODUCTION.

GEOLOGY is the science which investigates the history of the Earth. Its object is to trace the progress of our planet from the earliest beginnings of its separate existence, through its various stages of growth, down to the present condition of things. It unravels the complicated processes, involving vast geographical revolutions, by which each continent and country has been built up, tracing out the origin of their materials and the manner in which their existing outlines have been determined. It likewise follows into detail the varied sculpture of mountain and valley, crag and ravine.

Nor does this science confine itself merely to changes in the inorganic world. Geology shows that the present races of plants and animals are the descendants of other and very different races that once peopled the earth. It teaches that there has been a progress of the inhabitants, as well as one of the globe on which they have dwelt; that each successive period in the earth's history, since the introduction of living things, has been marked by characteristic types of the animal and vegetable kingdoms; and that, how imperfectly soever they may have been preserved or may be deciphered, materials exist for a history of life upon the planet. The geographical distribution of existing faunas and floras is often made clear and intelligible by geological evidence; and in a similar way, light is thrown upon some of the remoter phases in the history of man himself.

A subject so comprehensive as this must require a wide and varied basis of evidence. One of the characteristics of geology is to gather evidence from sources which, at first sight, seem far removed from its scope, and to seek aid from almost every other leading branch of science. Thus, in dealing with the earliest conditions of the planet, the geologist must fully avail himself of the labours of the astronomer. Whatever is ascertainable by telescope, spectroscope, or chemical analysis, regarding the constitution of other heavenly bodies, has a geological bearing. The experiments of the physicist, undertaken to determine conditions of matter and of energy, may sometimes be taken as the starting-point of geological investigation. The work of the chemical laboratory forms the foundation of a vast and increasing mass of geological inquiry. To the botanist, the zoologist, even to the unscientific, if observant, traveller by land or sea, the geologist turns for information and assistance.

But while thus culling freely from the dominions of other sciences, geology claims, as its peculiar territory, the rocky framework of the globe. In the materials composing that framework, their composition and arrangement, the processes of their formation, the changes which they have individually undergone, and the grand terrestrial revolutions to which they bear witness, lie the main data of geological history. It is the task of the geologist to group these elements in such a way that they may be made to yield up their evidence as to the march of events in the evolution of the planet. He finds that they have in large measure arranged themselves in chronological sequence,—the oldest lying at the bottom and the newest at the top. Relics of an ancient sea-floor are overlain with traces of a vanished land-surface, these are in turn covered by the deposits of a former lake, above which once more appear proofs of the return of the sea. Among these rocky records, too, lie the lavas and ashes of long-extinct volcanoes. The ripple left upon a sandy beach, the cracks formed by the sun's heat upon the muddy bottom of a dried-up pool, the very imprint of the drops of a passing rain-shower, have all been accurately preserved, and often bear witness to geographical conditions widely different from those that exist where such markings are now found.

But it is mainly by the remains of plants and animals imbedded in the rocks that the geologist is guided in unravelling the chronological succession of geological changes. He has found that a certain order of appearance characterises these organic remains; that each successive group of rocks is marked by its own special types of life; that these types can be recognised, and the rocks in which they occur can be correlated, even in distant countries, where no other means of comparison are available. At one moment, he has to deal with the bones of some large mammal scattered through a deposit of superficial gravel, at another time, with the minute foraminifers and ostracods of an upraised sea-bottom. Corals and crinoids, crowded and crushed into a massive limestone on the spot where they lived and died, ferns and terrestrial plants matted together into a bed of coal where they originally grew, the scattered shells of a submarine sand-bank, the snails and lizards that left their mouldering remains within a hollow tree, the insects that have been imprisoned within the exuding resin of old forests, the footprints of birds and quadrupeds, or the trails of worms left upon former shores—these, and innumerable other pieces of evidence, enable the geologist to realise in some measure what the vegetable and animal life of successive periods has been, and what geographical changes the site of every land has undergone.

It is evident that to deal successfully with these varied materials, a considerable acquaintance with different branches of science is desirable. The fuller and more accurate the knowledge which the geologist has of kindred branches of inquiry, the more interesting and fruitful will be his own researches. From its very nature, geology demands on the part of its votaries, wide sympathy with investigation in almost every branch of natural science. Especially necessary is a tolerably large acquaintance with the processes now at work in changing the surface of the earth, and of at least those forms of plant and animal life whose remains are apt to be preserved in geological deposits, or which, in their structure and habitat, enable us to realise what their forerunners were.

It has often been insisted upon that the Present is the key to the Past; and in a wide sense this assertion is eminently true. Only in proportion as we understand the present, where everything is open on all sides to the fullest investigation, can we expect to decipher the past, where so much is obscure, imperfectly preserved, or not preserved at all. A study of the existing economy of nature ought evidently to be the foundation of the geologist's training.

While, however, the present condition of things is thus employed, we must obviously be on our guard against the danger of unconsciously assuming that the phase of nature's operations which we now witness has been the same in all past time; that geological changes have taken place, in former ages, in the manner and on the scale which we behold to-day, and that at the present time all the great geological processes, which have produced changes in past eras of the earth's history, are still existent and active. Of course, we may assume this uniformity of action, and use the assumption as a working hypothesis. But it ought not to be allowed a firmer footing, nor on any account be suffered to blind us to the obvious truth that the few centuries, wherein man has been observing nature, form much too brief an interval by which to measure the intensity of geological action in all past time. For aught we can tell, the present is an era of quietude and slow change, compared with some of the eras that have preceded it. Nor can we be sure that when we have explored every geological process now in progress, we have exhausted all the causes of change which, even in comparatively recent times, have been at work.

In dealing with the Geological Record, as the accessible solid part of the globe is called, we cannot too vividly realise that, at the best, it forms but an imperfect chronicle. Geological history cannot be compiled from a full and continuous series of documents. Owing to the very nature of its origin, the record is necessarily from the first fragmentary, and it has been further mutilated and obscured by the revolutions of successive ages. Even where the chronicle of events is continuous, it is of very unequal value in different places. In one case, for example, it may present us with an unbroken succession of deposits, many thousands of feet in thickness, from which, however, only a few meagre facts as to geological history can be gleaned. In another instance, it brings before us, within the compass of a few yards, the evidence of a most varied and complicated series of changes in physical geography, as well as an abundant and interesting suite of organic remains. These and other characteristics of the geological record will become more apparent and intelligible to the student as he proceeds in the study of the science.

In the present volume the subject will be distributed under the following leading divisions.

1. *The Cosmical Aspects of Geology.*—It is desirable to realise some of the more important relations of the earth to the other members of the solar system, of which it forms a part, seeing that geological phenomena are largely the result of these relations. The form and motions of the planet may be briefly touched upon, and attention should be directed to the way in which these planetary movements influence geological change. The light cast upon the early history of the earth by researches into the composition of the sun and stars deserves notice here.

2. *Geognosy—An Inquiry into the Materials of the Earth's Substance.*—This division describes the constituent parts of the earth, its envelopes of air and water, its solid crust, and the probable condition of its interior. Especially, it directs attention to the more important minerals of the crust, and the chief rocks of which that crust is built up. In this way, it lays a foundation of knowledge regarding the nature of the materials constituting the mass of the globe, whence we may next proceed to investigate the processes by which these materials are produced and altered.

3. *Dynamical Geology* embraces an investigation of the operations which lead to the formation, alteration, and disturbance of rocks, and calls in the aid of physical and chemical experiment in elucidation of these operations. It considers the nature and operation of the processes that have determined the distribution of sea and land, and have moulded the forms of the terrestrial ridges and depressions. It further investigates the geological changes which are in progress over the surface of the land and floor of the sea, whether these are due to subterranean disturbance, or to the effect of operations above ground. Such an inquiry necessitates a careful study of the existing economy of nature, and forms a fitting introduction to the investigation of the geological changes of former periods. This and the previous section, including most of what is embraced under Physical Geography and Petrogeny or Geogeny, will here be discussed more in detail than is usual in geological treatises.

4. *Geotectonic, or Structural Geology—the Architecture of the Earth.*—This section of the investigation, applying the results arrived at in the previous division, discusses the actual arrangement of the various materials composing the crust of the earth. It proves that some have been formed in beds or strata, whether by the deposit of sediment on the floor of the sea, or by the slow aggregation of organic forms, that others have been poured out from subterranean sources in sheets of molten rock, or in showers of loose dust, which have been built up into mountains and plateaux. It further shows that rocks originally laid down in almost horizontal beds have subsequently been crumpled, contorted, dislocated, invaded by igneous masses from below, and rendered sometimes crystalline. It teaches, too, that wherever exposed above sea-level, they have been incessantly worn down, and have often been depressed, so that older lie buried beneath later accumulations.

5. *Palæontological Geology.*—This branch of the subject deals with the organic forms which are found preserved in the rocks of the crust of the earth. It includes such questions as the manner in which the remains of plants and animals are entombed in sedimentary accumulations, the relations between extinct and living types, the laws which appear to have governed the distribution of life in time and in space, the nature and use of the evidence from organic remains regarding former conditions of physical geography, and the relative importance of different genera of animals and plants in geological inquiry.

6. *Stratigraphical Geology.*—This section might be called Geological History, or Historical Geology. It works out the chronological succession of the great formations of the earth's crust, and endeavours to trace the sequence of events of which they contain the record. More particularly, it determines the order of succession of the various plants and animals which in past time have peopled the earth, and thus, by ascertaining what has been the grand march of life upon the planet, seeks to unravel the story of the earth as made known by the rocks of the crust. Further, by comparing the sequence of rocks in one country with that of those in another, it furnishes materials for enabling us to picture the successive stages in the geographical evolution of the various portions of the earth's surface.

7. *Physiographical Geology,* starting from the basis of fact laid down by stratigraphical geology regarding former geographical changes, embraces an inquiry into the history of the present features of the earth's surface —continental ridges and ocean basins, plains, valleys, and mountains. It investigates the structure of mountains and valleys, compares the mountains of different countries, and ascertains the relative geological dates of their upheaval. It explains the causes on which local differences of scenery depend, and shows under what very different circumstances, and at what widely separated intervals, the varied contours, even of a single country, have been produced.

BOOK I.

COSMICAL ASPECTS OF GEOLOGY.

BEFORE geology had attained to the position of an inductive science, it was customary to begin all investigations into the history of the earth by propounding or adopting some more or less fanciful hypothesis, in explanation of the origin of our planet or of the universe. Such preliminary notions were looked upon as essential to a right understanding of the manner in which the materials of the globe had been put together. To the illustrious James Hutton (1785) geologists are indebted, if not for originating, at least for strenuously upholding the doctrine that it is no part of the province of geology to discuss the origin of things. He taught them that in the materials from which geological evidence is to be compiled there can be found "no traces of a beginning, no prospect of an end." In England, mainly to the influence of the school which he founded, and to the subsequent rise of the Geological Society (1807), which resolved to collect facts instead of fighting over hypotheses, is due the disappearance of the crude and unscientific cosmologies of previous centuries.

But there can now be little doubt that in the reaction against the visionary and often grotesque speculations of earlier writers, geologists were carried too far in an opposite direction. In allowing themselves to believe that geology had nothing to do with questions of cosmogony, they gradually grew up in the conviction that such questions could never be other than mere speculation, interesting or amusing as a theme for the employment of the fancy, but hardly coming within the domain of sober and inductive science. Nor would they soon have been awakened out of this belief by anything in their own science. It is still true that in the data with which they are accustomed to deal, as comprising the sum of geological evidence, there can be found no trace of a beginning, though there is ample proof of constant, upward progression from some invisible starting-point. The oldest rocks which have been discovered on any part of the globe have possibly been derived from other rocks older than themselves. Geology by itself has not yet revealed, and is little likely ever to reveal, a portion of the first solid crust of our globe. If, then, geological history is to be compiled from direct evidence furnished by the rocks of the earth, it cannot begin at the beginning of things, but must be content to date its first chapter from the earliest period of which any record has been preserved among the rocks.

Nevertheless, though, in its usual restricted sense, geology has been, and must ever be, unable to reveal the earliest history of our planet, it no longer ignores, as mere speculation, what is attempted in this subject by its sister sciences. Astronomy, physics and chemistry have in late years all contributed to cast much light on the earliest stages of the earth's existence, previous to the beginning of what is commonly regarded as geological history. Whatever extends our knowledge of the former conditions of our globe may be legitimately claimed as part of the domain of geological inquiry. If Geology, therefore, is to continue worthy of its name as the science of the earth, it must take cognisance of these recent contributions from other sciences. It can no longer be content to begin its annals with the records of the oldest rocks, but must endeavour to grope its way through the ages which preceded the formation of any rocks. Thanks to the results achieved with the telescope, the spectroscope, and the chemical laboratory, the story of these earliest ages of our earth is every year becoming more definite and intelligible.

I. Relations of the Earth in the Solar System.

As a prelude to the study of the structure and history of the earth, some of the general relations of our planet to the solar system may here be noticed. The investigations of recent years, showing the community of substance between the different members of that system, have revived and have given a new form and meaning to the well-known nebular hypothesis of Kant, Laplace and W. Herschel, which sketched the progress of the system from the state of an original nebula to its existing condition of a central incandescent sun with surrounding cool planetary bodies. According to this hypothesis, the nebula, originally diffused at least as far as the furthest member of the system, began to condense towards the centre, and in so doing threw off or left behind successive rings. These, on disruption and further condensation, assumed the form of planets, sometimes with a further formation of rings, which in the case of Saturn remain, though in other planets they have broken up and united into satellites.

Accepting this view, we should expect the matter composing the various members of the solar system to be everywhere nearly the same. The fact of condensation round centres, however, indicates probable differences of density throughout the nebula. That the materials composing the nebula may have arranged themselves according to their respective densities, the lightest occupying the exterior, and the heaviest the interior of the mass, is suggested by a comparison of the densities of the various planets. These densities are usually estimated as in the following table, that of the earth being taken as the unit:—

Density of the Sun	0·25
,, Mercury	1·12
,, Venus	1·03
,, Earth	1·00
,, Mars	0·70
,, Jupiter	0·24
,, Saturn	0·13
,, Uranus	0·17
,, Neptune	0·16

It is to be observed, however, that "the densities here given are mean densities, assuming that the *apparent* size of the planet or sun is the *true* size, *i.e.*, making no allowance for thousands of miles deep of cloudy atmosphere. Hence the numbers for Jupiter, Saturn, and Uranus are certainly too small, that for the sun, much too small."[1] Taking the figures as they stand, while they do not indicate a strict progression in the diminution of density, they state that the planets near the sun possess a density about twice as great as that of granite, but that those lying towards the outer limits of the system are composed of matter as light as cork. Again, in some cases, a similar relation has been observed between the densities of the satellites and their primaries. The moon, for example, has a density little more than half that of the earth. The first satellite of Jupiter is less dense, though the other three are said to be more dense than the planet. Further, in the condition of the earth itself, a very light gaseous atmosphere forms the outer portion, beneath which lies a heavier layer of water, while within these two envelopes the materials forming the solid substance of the planet are so arranged that the outer layer or crust has only about half the density of the whole globe.

According to the hypothesis now under consideration it is conceived that, in the gradual condensation of the original nebula, each successive mass left behind represented the density of its parent shell, and consisted of progressively heavier matter.[2] The remoter planets, with their low densities and vast absorbing atmospheres, may be supposed to consist of metalloids, like the outer parts of the sun's atmosphere, while the interior planets are no doubt mainly metallic. The rupture of each planetary ring would, it is thought, raise the temperature of the resultant nebulous planet to such a height as to allow the vapours to rearrange themselves by degrees in successive layers, or rather shells, according to densities. And when the planet gave off a satellite, that body might be expected to possess the composition and density of the outer layers of its primary.[3]

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[1] Professor Tait, MS. note.

[2] On the origin of Satellites, see the researches of Prof. G. H. Darwin, *Phil. Trans.* (1879) clxx. p. 535. *Proc. Roy. Soc.* xxx. p. 1.

[3] Lockyer in Prestwich's *Inaugural Lecture*, Oxford, 1875, and in Manchester Lectures, *Why the Earth's Chemistry is as it is.* Readers interested in the historical development of geological opinion will find much suggestive matter bearing on the questions discussed above, in De la Beche's 'Researches in Theoretical Geology,' 1834,—a work notably in advance of its time.

For many years, the only evidence available as to the actual composition of other heavenly bodies than our own earth was furnished by the *meteorites*, or fallen stars, which from time to time have entered our atmosphere from planetary space, and have descended upon the surface of the globe.[1] Subjected to chemical analysis, these foreign bodies show considerable diversities of composition; but in no case have they yet revealed the existence of any element not already recognised among terrestrial materials. They have been classified in three groups: *Siderites*, composed chiefly of iron; *Siderolites*, consisting partly of iron and partly of various stony materials; and *Aerolites*, formed almost entirely of such stony minerals. Twenty-four of our elements have been detected in meteorites. Those most commonly found are iron, nickel, phosphorus, sulphur, carbon, oxygen, silicon, magnesium, calcium and aluminium. Less frequent or occurring in smaller quantities are hydrogen, nitrogen, chlorine, lithium, sodium, potassium, titanium, chromium, manganese, cobalt, arsenic, antimony, tin and copper. These various elements occur for the most part in a state of combination. The iron exists as an alloy with nickel, the phosphorus is combined with nickel and iron, the silicon is combined with oxygen and various bases. A few of the elements occur in a free state. Thus hydrogen and nitrogen are found as occluded gases and carbon as graphite, rarely as diamond. Of combinations of elements in meteorites some, not yet recognised among terrestrial minerals, comprise alloys of iron and nickel and various sulphides and silicates. But others have been identified with well-known minerals of the earth's crust, including olivine, enstatite and bronzite, diopside and augite, hornblende, anorthite and labradorite, magnetite and chromite, &c. There is likewise a carbonaceous group of meteorites containing carbon, both amorphous and as black diamond, also combined with hydrogen and oxygen, and in some cases combustible, with a bituminous smell. Some iron meteorites contain a large proportion of occluded hydrogen, nitrogen, or carbonic oxide, occasionally as much as six times the volume of the meteorite itself.

Various theories have been propounded as to the origin or source of those bodies which come to our planet from space. But at present we possess no satisfactory basis of fact on which to speculate. Whether these stones belong to the solar system, or, as seems more probable, reach us from remoter space, they prove that some at least of the elements and minerals with which we are familiar extend beyond our planet.

But, in recent years, a far more precise and generally available method of research into the composition of the heavenly bodies has been found in the application of the spectroscope. By means of this instrument, the light emitted from self-luminous bodies can be analysed in such a way as to show what elements are present in their intensely hot luminous vapour. When the light of the incandescent vapour of a metal is allowed to pass through a properly arranged prism, it is seen to give a spectrum consisting of transverse bright lines only. This is termed a *radiation-spectrum.* Each element appears to have its own characteristic arrangement of lines, which in general retain the same relative position, intensity and colours. Moreover, gases and the vapours of solid bodies are found to intercept those rays of light which they themselves emit. The spectrum of sodium-vapour, for example, shows among others two bright orange lines. If therefore white light, from some hotter light-source, passes through the vapour of sodium, these two bright lines become dark lines, the light being exactly cut off which would have been given out by the sodium itself. This is called an *absorption-spectrum.*

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[1] On meteorites consult Partsch, 'Die Meteoriten,' Vienna, 1843. Rose, *Abhand. königl. Akad.* Berlin, 1863. Rammelsberg, 'Die Chemische Natur der Meteoriten,' 1870-9. Tschermak, *Sitzb. Akad. Wissen.* Vienna (1875), lxxi.; 'Die Mikroskopische Beschaffenheit der Meteoriten,' Stuttgart, 1885. Daubrée, 'Etudes Synthétiques de Géologie Expérimentale,' 1879; *Compt. rend.* cvi. (1888), 1671-1682 (compare *Amer. Journ. Sci.* xlii. (1891), p. 413). S. Meunier, 'Le Ciel Géologique,' 1871; 'Météorites,' 1884. Brezina und Cohen, 'Die Structur und Zusammensetzung der Meteoreisen,' Stuttgart, 1886. W. Flight, *Geol. Mag.* 1875, *Pop. Sci. Rev. new ser.* i. p. 390. *Proc. Roy. Soc.* xxxiii. p. 343. A. W. Wright, *Amer. Journ.* ser. 3, xi. p. 253; xii. p. 165. L. Fletcher, 'An Introduction to the Study of Meteorites,' British Museum Catalogue, 1886.

From this method of examination, it has been inferred that many of the elements of which our earth is composed must exist in the state of incandescent vapour in the atmosphere of the sun. Thirty-two metals have been thus identified, including aluminium, barium, manganese, lead, calcium, cobalt, potassium, iron, zinc, copper, nickel, sodium and magnesium. These elements, or at least substances which give the same groups of lines as the terrestrial elements with which they have been identified, do not occur promiscuously diffused throughout the outer mass of the sun. According to Mr. Lockyer's first observations, they appear to succeed each other in relation to their respective densities. Thus the coronal atmosphere which, as seen in total eclipses, extends to so prodigious a distance beyond the disc of the sun, consists mainly of subincandescent hydrogen and another element which may be new. Beneath this external vaporous envelope lies the chromosphere, where the vapours of incandescent hydrogen, calcium and magnesium can be detected. Further inward the spot-zone shows the presence of sodium, titanium, &c.; while still lower, a layer (the *reversing* layer) of intensely hot vapours, lying probably next to the inner brilliant photosphere, gives spectroscopic evidence of the existence of incandescent iron, manganese, cobalt, nickel, copper, and other well-known terrestrial metals.[1]

It is to be observed, however, that in these spectroscopic researches the decomposition of the elements by electrical action was not considered. The conclusions embodied in the foregoing paragraph have been founded on the idea that the lines seen in the spectrum of any element are all due to the vibrations of the molecules of that element. But Mr. Lockyer has suggested that this view may after all be but a rough approximation to the truth; that it may be more accurate to say, as a result of the facts already acquired, that there exist basic elements common to calcium, iron, &c., and to the solar atmosphere, and that the spectrum of each body is a summation of the spectra of various molecular complexities which can exist at different temperatures, the simplest only being found in the hottest part of the sun.[1]

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[1] On spectroscopic research as applied to the sun, see Kirchhoff and Bunsen, 'Researches on Solar Spectrum,' &c., 1863; Ångström, 'Recherches sur le Spectre normal du Soleil'; Lockyer, 'Solar Physics,' 1873, and 'Studies in Spectrum Analysis' (International Series), 1878; Huggins and Miller, *Proc. Roy. Soc.* xii., *Phil. Trans.* 1864; Roscoe's 'Spectrum Analysis,' with authorities there cited. An ingenious theory to account for the conservation of solar energy was suggested by the late Sir C. W. Siemens (*Proc. Roy. Soc.* xxxiii. (1881) p. 389). It requires the presence of aqueous vapour and carbon compounds in stellar space, which are dissociated and drawn into the solar photosphere, where they burst into flame with a large development of heat, and then passing into aqueous vapour and carbonic anhydride or oxide, flow to the solar equator whence they are projected into space.

The spectroscope has likewise been successfully applied by Mr. Huggins and others to the observation of the fixed stars and nebulæ, with the result of establishing a similarity of elements between our own system and other bodies in sidereal space. In the radiation spectra of nebulæ, Mr. Huggins finds the hydrogen lines very prominent; and he conceives that they may be glowing masses of that element. Professor Tait has suggested, on the other hand, that they are more probably clouds of stones frequently colliding and thus giving off incandescent gases. Sir William Thomson (now Lord Kelvin) favours this view, which is further amply supported by spectroscopic observations. Among the fixed stars, absorption-spectra have been recognised, pointing to a structure resembling that of our sun, viz., an incandescent nucleus which may be solid or liquid or of very highly compressed gas, but which gives a continuous spectrum and which is surrounded with an atmosphere of glowing vapour.[2] Those stars which show the simplest spectra are believed to have the highest temperature, and in proportion as they cool their materials will become more and more differentiated into what we call elements. The most brilliant or hottest stars show in their spectra only the lines of gases, as hydrogen. Cooler stars, like our sun, give indications of the presence, in addition, of the metals—magnesium, sodium, calcium, iron. A still lower temperature is marked by the appearance of the other metals, metalloids, and compounds.[3] The sun would thus be a star considerably advanced in the process of differentiation or association of its atoms. It contains, so far as we know, no metalloid except carbon, and possibly oxygen, nor any compound, while stars like Sirius show the presence only of hydrogen, with but a feeble proportion of metallic vapours; and on the other hand, the red stars indicate by their spectra that their metallic vapours have entered into combination, whence it is inferred that their temperature is lower than that of our sun.

More recently, however, another view of the evolution of stars has been propounded by Mr. Lockyer. He conceives that all self-luminous cosmical bodies are composed either of swarms of meteorites, or of masses of vapour produced by collisions of meteorites; that stars, comets and nebulæ are only different phases of the same series of changes; that where the temperature of a star is increasing the star consists of a meteor-swarm, which by constant collision of its individual meteorites is gradually being vapourised by heat; and that after volatilisation cooling sets in and the vapour finally condenses into a globe.[1]

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[1] See also the opposite views of Dewar and Liveing, *Pro. Roy. Soc.* xxx. p. 93, and H. W. Vogel, *Nature*, xxvii. p. 233.

[2] Huggins, *Proc. Roy. Soc.* 1863-66, and *Brit. Assoc. Lecture* (Nottingham, 1866); Huggins and Miller, *Phil. Trans.* 1864.

[3] Lockyer, *Comptes rendus*, Dec. 1873.

II. Form and Size of the Earth.

Further confirmation of some of the foregoing views as to the order of planetary evolution is furnished by the form of the earth and the arrangment of its component materials.

That the earth is an oblate spheroid, and not a perfectly spherical globe, was discovered and demonstrated by Newton. He even calculated the amount of ellipticity long before any measurement had confirmed such a conclusion. During the present century numerous arcs of the meridian have been measured, chiefly in the northern hemisphere. From a series made by different observers between the latitudes of Sweden and the Cape of Good Hope, Bessel obtained the following data for the dimensions of the earth:—

Equatorial diameter . .	41,847,192 feet, or	7925·604 miles.
Polar diameter . . .	41,707,314 ,,	7899·114 ,,
Amount of polar flattening .	139,768 ,,	26·471 ,,

The equatorial circumference is thus a little less than 25,000 miles, and the difference between the polar and equatorial diameters (nearly 26½ miles) amounts to about $\frac{1}{300}$th of the equatorial diameter.[2] More recently, however, it has been shown that the oblate spheroid indicated by these measurements is not a symmetrical body, the equatorial circumference being an ellipse instead of a circle. The greater axis of the equator lies in long. 8° 15′ W.—a meridian passing through Ireland, Portugal, and the north-west corner of Africa, and cutting off the north-east corner of Asia in the opposite hemisphere.[3]

The polar flattening, established by measurement and calculation as that which would necessarily have been assumed by an originally plastic globe in obedience to the movement of rotation, has been cited as evidence that the earth was once in a plastic condition. Taken in connection with the analogies supplied by the sun and other heavenly bodies, this inference appeared to be well grounded.[4] More recently, however, it has been contended that even in a truly solid body a polar flattening might be developed under the influence of rotation.[1]

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[1] 'The Meteoritic Hypothesis,' 1890.

[2] Herschel, 'Astronomy,' p. 139.

[3] A. R. Clarke, *Phil. Mag.* August 1878; *Encyclopædia Britannica*, 9th edit. x. 172.

[4] It was opposed by Mohr ('Geschichte der Erde,' p. 472), who, adopting a suggestion long ago made by Playfair, endeavoured to show that the polar flattening can be accounted for by greater denudation of the polar tracts, exposed as these have been by the heaping up of the oceanic waters towards the equator in consequence of rotation. He dwelt chiefly on the effects of glaciers in lowering the land, but as Pfaff has pointed out, the work of erosion is chiefly performed by other atmospheric forces that operate rather towards the

Though the general spheroidal form of our planet, and probably the general distribution of sea and land, are referable to the early effects of rotation on a fluid or viscous mass, it is certain that the present details of its surface-contours are of comparatively recent date. Speculations have been made as to what may have been the earliest character of the solid surface, whether it was smooth or rough, and particularly whether it was marked by any indication of the existing continental elevations and oceanic depressions. So far as we can reason from geological evidence, there is no proof of any uniform superficies having ever existed. Most probably the first formed crust broke up irregularly, and not until after many successive corrugations did the surface acquire stability. Some writers have imagined that at first the ocean spread over the whole surface of the planet. But of this there is not only no evidence, but good reason for believing that it never could have taken place. As will be alluded to in a later page, the preponderance of water in the southern hemisphere, seems to indicate some excess of density in that hemisphere. This excess can hardly have been produced by any change since the materials of the interior ceased to be mobile; it must therefore be at least as ancient as the condensation of water on the earth's surface. Hence there was probably from the beginning a tendency in the ocean to accumulate in the southern rather than in the northern hemisphere.

That land existed from the earliest ages of which we have any record in rock-formations, is evident from the obvious fact that these formations themselves consist in great measure of materials derived from the waste of land. When the student, in a later part of this volume, is presented with the proofs of the existence of enormous masses of sedimentary deposits, even among some of the oldest geological systems, he will perceive how important must have been the tracts of land that could furnish such piles of detritus.

The tendency of modern research is to give probability to the conception, first outlined by Kant, that not only in our own solar system, but throughout the regions of space, there has been a common plan of evolution, and that the matter diffused through space in nebulæ, stars, and planets is substantially the same as that with which we are familiar. Hence the study of the structure and probable history of the sun and the other heavenly bodies comes to possess an evident geological interest, seeing that it may yet enable us to carry back the story of our planet far beyond the domain of ordinary geological evidence, and upon data not less trustworthy than those furnished by the rocks of the earth's crust.

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equator than the poles ('Allgemeine Geologie als exacte Wissenschaft,' p. 6). Compare Naumann, *Neues Jahrb.* 1871, p. 250. Nevertheless, Mohr undoubtedly recalled attention to a conceivable cause by which, in spite of polar elevation or equatorial subsidence, the external form of the planet might be preserved.

[1] See in particular the papers by Mr. C. Chree. *Phil. Mag.* 1891, pp. 233 and 342.

III. THE MOVEMENTS OF THE EARTH IN THEIR GEOLOGICAL RELATIONS.

We are here concerned with the earth's motions in so far only as they materially influence the progress of geological phenomena.

§ 1. **Rotation.**—In consequence of its angular momentum at its original separation, the earth rotates on its axis. The rate of rotation has once been much more rapid than it now is (p. 21). At present a complete rotation is performed in about twenty-four hours, and to it is due the succession of day and night. So far as observation has yet gone, this movement is uniform, though recent calculations of the influence of the tides in retarding rotation tend to show that a very slow diminution of the angular velocity is in progress. If this be so, the length of the day and night will slowly increase until finally the duration of the day and that of the year will be equal. The earth will then have reached the condition into which the moon has passed relatively to the earth, one half being in continual day, the other in perpetual night.

The linear velocity due to rotation varies in different places, according to their position on the surface of the planet. At each pole there can be no velocity, but from these two points towards the equator there is a continually increasing rapidity of motion, till at the equator it is equal to a rate of 507 yards in a second.

To the rotation of the earth are due certain remarkable influences upon currents of air circulating either towards the equator or towards the poles. Currents which move from polar latitudes travel from parts of the earth's surface where the velocity due to rotation is small, to others where it is great. Hence they lag behind, and their course is bent more and more westward. An air current, quitting the north polar or north temperate regions as a north wind, is deflected out of its course, and becomes a north-east wind. On the opposite side of the equator, a similar current setting out straight for the equator, is changed into a south-east wind. Hence, as is well-known, the Trade-winds have their characteristic westward deflection. On the other hand, a current setting out northwards or southwards from the equator, passes into regions having a less velocity due to rotation than it possesses itself, and hence it travels on in advance and appears to be gradually deflected eastward. The aerial currents, blowing steadily across the surface of the ocean towards the equator, produce oceanic currents which unite to form the westward-flowing Equatorial current.

It has been maintained by Von Baer,[1] that a certain deflection is experienced by rivers that flow in a meridional direction, like the Volga and Irtisch. Those travelling polewards are asserted to press upon their eastern rather than their western banks, while those which run in the opposite direction are stated to be thrown more against the western than the eastern. When, however, we consider the comparatively small volume, slow motion, and continually meandering course of rivers, it may reasonably be doubted whether this *vera causa* can have had much effect generally in modifying the form of river-channels.

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[1] "Ueber ein allgemeines Gesetz in der Gestaltung der Flussbetten." *Bull. Acad. St. Pétersbourg*, ii. (1860). See also Ferrel on the motion of fluids and solids relatively to the earth's surface, *Camb.* (*Mass.*) *Math. Monthly*, vols. i. and ii. (1859-60) ; Dulk, *Z. Deutsch. Geol. Ges.* xxxi. (1879) p. 224. The River Irtisch is said in flowing northward to have cut so much into its right bank that villages are gradually driven eastwards, Demiansk having been shifted about a mile in 240 years (*Nature*, xv. p. 207). But this may be accounted for by local causes. See an excellent paper on this subject with special reference to the régime of some rivers in northern Germany, by F. Klockmann, *Jahrb. Preuss. Geol. Landesanst.* 1882 ; also E. Dunker, *Zeitsch. für die gesammten Naturwissenschaften*, 1875, p. 463 ; G. K. Gilbert, *Amer. Journ. Sci.* xxvii. (1884) p. 427.

§ 2. **Revolution.**—Besides turning on its axis, the globe performs a movement round the sun, termed revolution. This movement, accomplished in rather more than 365 days, determines for us the length of our year, which is, in fact, merely the time required for one complete revolution. The path or orbit followed by the earth round the sun is not a perfect circle but an ellipse, with the sun in one of the foci, the mean distance of the earth from the sun being 92,800,000, the present aphelion distance 94,500,000, and the perihelion distance 91,250,000 miles. By slow secular variations, the form of the orbit alternately approaches to and recedes from that of a circle. At the nearest possible approach between the two bodies, owing to change in the ellipticity of the orbit, the earth is 14,368,200 miles nearer the sun than when at its greatest possible distance. These maxima and minima of distance occur at vast intervals of time.[1] The last considerable eccentricity took place about 200,000 years ago, and the previous one more than half a million years earlier. Since the amount of heat received by the earth from the sun is inversely as the square of the distance, eccentricity may have had in past time much effect upon the climate of the earth, as will be pointed out further on (§ 8).

§ 3. **Precession of the Equinoxes.**—If the axis of the earth were perpendicular to the plane of its orbit, there would be equal day and night all the year round. But it is really inclined from that position at an angle of 23° 27′ 21″. Hence our hemisphere is alternately presented to and turned away from the sun, and, in this way, brings the familiar alternation of the seasons. Again, were the earth a perfect sphere, of uniform density throughout, the position of its axis of rotation would not be changed by attractions of external bodies. But owing to the protuberance along the equatorial regions, the attraction chiefly of the moon and sun tends to pull the axis aside, or to make it describe a conical movement, like that of the axis of a top, round the vertical. Hence each pole points successively to different stars. This movement, called the precession of the equinoxes, in combination with another smaller movement, due to the attraction of the moon (called *nutation*), completes its cycle in 21,000 years, the annual total advance of the equinox amounting to 62″. At present the winter in the northern hemisphere coincides with the earth's nearest approach to the sun, or *perihelion*. In 10,500 years hence it will take place when the earth is at the farthest part of its orbit from the sun, or in *aphelion*. This movement may have had great importance in connection with former secular variations in the eccentricity of the orbit (§ 8).

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[1] See Croll's 'Climate and Time,' chaps. iv., xix.

§ 4. **Change in the Obliquity of the Ecliptic.**—The angle at which the axis of the earth is inclined to the plane of its orbit does not remain strictly constant. It oscillates through long periods of time to the extent of about a degree and a half, or perhaps a little more, on either side of the mean. According to Dr. Croll,[1] this oscillation must have considerably affected former conditions of climate on the earth, since, when the obliquity is at its maximum, the polar regions receive about eight and a half days' more of heat than they do at present—that is, about as much heat as lat. 76° enjoys at this day. This movement must have augmented the geological effects of precession, to which reference has just been made, and which are described in § 8.

§ 5. **Stability of the Earth's Axis.**—That the axis of the earth's rotation has successively shifted, and consequently that the poles have wandered to different points on the surface of the globe, has been maintained by geologists as the only possible explanation of certain remarkable conditions of climate, which can be proved to have formerly obtained within the Arctic Circle. Even as far north as lat. 81° 45′, abundant remains of a vegetation indicative of a warm climate, and including a bed of coal 25 to 30 feet thick, have been found *in situ*.[2] It is contended that when these plants lived, the ground could not have been permanently frozen or covered for most of the year with thick snow. In explanation of the difficulty, it has been suggested that the north pole did not occupy its present position, and that the locality where the plants occur lay in more southerly latitudes. Without at present entering on the discussion of the question whether the geological evidence necessarily requires so important a geographical change, let us consider how far a shifting of the axis of rotation has been a possible cause of change during that section of geological time for which there are records among the stratified rocks.

From the time of Laplace,[3] astronomers have strenuously denied the possibility of any sensible change in the position of the axis of rotation. It has been urged that, since the planet acquired its present oblate spheroidal form, nothing but an utterly incredible amount of deformation could overcome the greater centrifugal force of the equatorial protuberance. It is certain, however, that the axis of rotation does not strictly coincide with the principal axis of inertia. Though the angular difference between them must always have been small, we can, without having recourse to any extramundane influence, recognise two causes which, whether or not they may suffice to produce any change in the position of the main axis of inertia, undoubtedly tend to do so. In the first place, a widespread upheaval or depression of certain unsymmetrically arranged portions of the surface to a considerable amount would tend to shift that axis. In the second place, an analogous result might arise from the denudation of continental masses of land, and the consequent filling up of sea-basins. Lord Kelvin (Sir William Thomson) freely concedes the physical possibility of such changes. "We may not merely admit," he says, "but assert as highly probable, that the axis of maximum inertia and axis of rotation, always very near one another, may have been in ancient times very far from their present geographical position, and may have gradually shifted through 10, 20, 30, 40, or more degrees, without at any time any perceptible sudden disturbance of either land or water."[1] But though, in the earlier ages of the planet's history, stupendous deformations may have occurred, and the axis of rotation may have often shifted, it is only the alterations which can possibly have occurred during the accumulation of the stratified rocks, that need to be taken into account in connection with the evidence of changes of climate during geological history. If it can be shown, therefore, that the geographical revolutions necessary to shift the axis are incredibly stupendous in amount, improbable in their distribution, and not really demanded by geological evidence, we may reasonably withhold our belief from this alleged cause of the changes of climate during the periods of time embraced by geological records.

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[1] Croll, *Trans. Geol. Soc. Glasgow*, ii. 177. 'Climate and Time,' chap. xxv.

[2] Fielden and Heer, *Quart. Journ. Geol. Soc.* Nov. 1877.

[3] 'Mécanique Céleste,' tome v. p. 14.

It has been estimated by Lord Kelvin "that an elevation of 600 feet, over a tract of the earth's surface 1000 miles square and 10 miles in thickness, would only alter the position of the principal axis by one-third of a second, or 34 feet."[2] Prof. George Darwin has shown that, on the supposition of the earth's complete rigidity, no redistribution of matter in new continents could ever shift the pole from its primitive position more than 3°, but that, if its degree of rigidity is consistent with a periodical re-adjustment to a new form of equilibrium, the pole may have wandered some 10° or 15° from its primitive position, or have made a smaller excursion and returned to near its old place. In order, however, that these maximum effects should be produced, it would be necessary that each elevated area should have an area of depression corresponding in size and diametrically opposite to it, that they should lie on the same complete meridian, and that they should both be situated in lat. 45°. With all these coincident favourable circumstances, an effective elevation of $\frac{1}{300}$ of the earth's surface to the extent of 10,000 feet would shift the pole $11\frac{1}{3}'$; a similar elevation of $\frac{1}{20}$ would move it $1° 46\frac{1}{2}'$; of $\frac{1}{10}$, $3° 17'$; and of $\frac{1}{2}$, $8° 4\frac{1}{2}'$. Mr. Darwin admits these to be superior limits to what is possible, and that, on the supposition of intumescence or contraction under the regions in question, the deflection of the pole might be reduced to a quite insignificant amount.[3]

Under the most favourable conditions, therefore, the possible amount of deviation of the pole from its first position would appear to have been too small to have seriously influenced the climates of the globe within geological history. If we grant that these changes were cumulative, and that the superior limit of deflection was reached only after a long series of concurrent elevations and depressions, we must suppose that no movements took place elsewhere to counteract the effect of those about lat. 45° in the two hemispheres. But this is hardly credible. A glance at a geographical globe suffices to show how large a mass of land exists now both to the north and south of that latitude, especially in the northern hemisphere, and that the deepest parts of the ocean are not antipodal to the greatest heights of the land. These features of the earth's surface are of old standing. There seems, indeed, to be no geological evidence in favour of any such geographical changes as could have produced even the comparatively small displacement of the axis considered possible by Prof. Darwin.

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[1] *Brit. Assoc. Rep.* (1876), Sections, p. 11.

[2] *Trans. Geol. Soc. Glasgow*, iv. p. 313. The situation of the supposed area of upheaval on the earth's surface is not stated.

[3] *Phil. Trans.* Nov. 1876.

In an ingenious suggestion, Sir John Evans contended that, even without any sensible change in the position of the axis of rotation of the nucleus of the globe, there might be very considerable changes of latitude due to disturbance of the equilibrium of the outer portion or shell by the upheaval or removal of masses of land between the equator and the poles, and to the consequent sliding of the shell over the nucleus until the equilibrium was restored.[1] Subsequently he precisely formulated his hypothesis as a question to be determined mathematically;[2] and the solution of the problem was worked out by the Rev. J. F. Twisden, who arrived at the conclusion that even the large amount of geographical change postulated by Dr. Evans could only displace the earth's axis of figure to the extent of less than 10′ of angle, that a displacement of as much as 10° or 15° could be effected only if the heights and depths of the areas elevated and depressed exceeded by many times the heights of the highest mountains, that under no circumstances could a displacement of 20° be effected by a transfer of matter of less amount than about a sixth part of the whole equatorial bulge, and that even this extreme amount would not necessarily alter the position of the axis of figure.[3]

Against any hypothesis which assumes a thin crust enclosing a liquid or viscous interior, weighty and, indeed, insuperable objections have been urged. It has been suggested, however, that the almost universal traces of present or former volcanic action, the evidence from the compressed strata in mountain regions that the crust of the earth must have a capacity for slipping towards certain lines, the great amount of horizontal compression of strata which can be provèd to have been accomplished, and the secular changes of climate—notably the former warm climate near the north pole—furnish grounds for inquiry whether the doctrine of a fluid substratum over a rigid nucleus, which has been urged by several able writers, would not be compatible with mechanical considerations, and whether, under these circumstances, changes in latitude would not result from unequal thickening of the crust.[1] This question of the internal condition of the globe is discussed at p. 47.

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[1] *Proc. Roy. Soc.* xv. (1867), p. 46.

[2] *Q. J. Geol. Soc.* xxxii. (1876), p. 62.

[3] *Q. J. Geol. Soc.* xxxiv. (1878), p. 41. See also E. Hill, *Geol. Mag.* v. (2nd ser.) pp. 262, 479. O. Fisher, *op. cit.* pp. 291, 551.

§ 6. **Changes of the Earth's Centre of Gravity.**—If the centre of gravity in our planet, as pointed out by Herschel, be not coincident with the centre of figure, but lies somewhat to the south of it, any variation in its position will affect the ocean, which of course adjusts itself in relation to the earth's centre of gravity. How far any redistribution of the matter within the earth, in such a way as to affect the present equilibrium, is now possible, we cannot tell. But certain revolutions at the surface may from time to time produce changes of this kind. The accumulation of ice which, as will be immediately described (§ 8), is believed to gather round one pole during the maximum of eccentricity, will displace the centre of gravity, and, as the result of this change, will raise the level of the ocean in the glacial hemisphere.[2] The late Dr. Croll estimated that, if the present mass of ice in the southern hemisphere is taken at 1000 feet thick extending down to lat. 60°, the transference of this mass to the northern hemisphere would raise the level of the sea 80 feet at the north pole. Other methods of calculation give different results. Mr. Heath put the rise at 128 feet; Archdeacon Pratt made it more; while the Rev. O. Fisher gave it at 409 feet.[3] Subsequently, in returning to this question, Dr. Croll remarked "that the removal of two miles of ice from the Antarctic continent [and at present the mass of ice there is probably thicker than that] would displace the centre of gravity 190 feet, and the formation of a mass of ice equal to the one-half of this, on the Arctic regions, would carry the centre of gravity 95 feet farther; giving in all a total displacement of 285 feet, thus producing a rise of level at the north pole of 285 feet, and in the latitude of Edinburgh of 234 feet." A very considerable additional displacement would arise from the increment of water to the mass of the ocean by the melting of the ice. Supposing half of the two miles of Antarctic ice to be replaced by an ice-cap of similar extent and one mile thick in the northern hemisphere, the other half being melted into water and increasing the mass of the ocean, Dr. Croll estimated that from this scource an extra rise of 200 feet would take place in the general ocean level, so that there would be a rise of 485 feet at the north pole, and 434 feet in the latitude of Edinburgh.[4] An intermittent submergence and emergence of the low polar lands might be due to the alternate shifting of the centre of gravity.

To what extent this cause has actually come into operation in past time cannot at present be determined. It has been suggested that the "raised beaches," shore-lines (*strand-linien*), or old sea-terraces, so numerous at various heights in the north-west of Europe, might be due to the transference of the oceanic waters, and not to any subterranean movement, as generally believed. Had they been due to such a general cause, they ought to have shown evidence of a gradual and uniform decline in elevation from north to south, with only such local variations as might be accounted for by the influence of masses of high land or other local cause. No such feature, however, has been satisfactorily established.[1] On the contrary, the levels of the terraces vary within comparatively short distances. Though numerous on both sides of Scotland, they disappear further north among the Orkney and Shetland islands, although these localities were admirably adapted for their formation and preservation.[2] The conclusion may be drawn that the "raised beaches" cannot be adduced as evidence of changes of the earth's centre of gravity, but are due to local and irregularly acting causes. (See Book III. Part I. Section iii. § 1, where this subject is more fully discussed.)

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[1] O. Fisher, *Geol. Mag.* 1878, p. 552, 'Physics of the Earth's Crust,' 1882; 2nd Edition 1889.

[2] Adhemar, 'Révolutions de la Mer,' 1840.

[3] Croll, in *Reader* for 2nd September, 1865, and *Phil. Mag.* April, 1866; Heath, *Phil. Mag.* April, 1869; Pratt, *Phil. Mag.* March, 1866; Fisher, *Reader*, 10th February, 1866.

[4] Croll, *Geol. Mag.* new series, i. (1874), p. 347; 'Climate and Time,' chaps. xxiii. and xxiv. and *postea*, p. 286. Consult also Fisher, *Phil. Mag.* xxxiv. (October, 1892), p. 337.

§ 7. **Results of the Attractive Influence of Sun and Moon on the Geological Condition of the Earth.**—Many speculations have been offered to account for supposed former greater intensity of geological activity on the surface of the globe. Two causes for such greater intensity may be adduced. In the first place, if the earth has cooled down from an original molten condition, it has lost, in cooling, a vast amount of potential geological energy. It does not necessarily follow, however, that the geological phenomena resulting from internal temperature have, during the time recorded in the accessible part of the earth's crust, been steadily decreasing in magnitude. We might, on the contrary, contend that the increased resistance of a thickening cooled crust may rather have hitherto intensified the manifestations of subterranean activity, by augmenting the resistance to be overcome. In the second place, the earth may have been once more powerfully affected by external causes, such as the greater heat of the sun, and the greater proximity of the moon. That the formerly larger amount of solar heat received by the surface of our planet must have produced warmer climates and more rapid evaporation, with greater rainfall and the important chain of geological changes which such an increase would introduce, appears in every way probable, though the geologist has not yet been able to observe any indisputable indication of such a former intensity of superficial changes.

Prof. Darwin, in investigating the bodily tides of viscous spheroids, has brought forward some remarkable results bearing on the question of the possibility that geological operations, both internal and superficial, may have been once greatly more gigantic and rapid than they are now.[3] He assumes the earth to be a homogeneous spheroid and to have possessed a certain small viscosity,[4] and he calculates the internal tidal friction in such a mass exposed to the attraction of moon and sun, and the consequences which these bodily tides have produced. He finds that the length of our day and month have greatly increased, that the moon's distance has likewise augmented, that the obliquity of the ecliptic has diminished, that a large amount of hypogene heat has been generated by the internal tidal friction, and that these changes may all have transpired within comparatively so short a period (57,000,000 years) as to place them quite probably within the limits of ordinary geological history. According to his estimate, 46,300,000 years ago the length of the sidereal day was fifteen and a half hours, the moon's distance in mean radii of the earth was 46·8 as compared with 60·4 at the present time. But 56,810,000 years back, the length of a day was only 6$\frac{3}{4}$ hours, or less than a quarter of its present value, the moon's distance was only nine earth's radii, while the lunar month lasted not more than about a day and a half (1·58), or $\frac{1}{17}$ of its present duration. He arrives at the deduction that the energy lost by internal tidal friction in the earth's mass is converted into heat at such a rate that the amount lost during 57,000,000 years, if it were all applied at once, and if the earth had the specific heat of iron, would raise the temperature of the whole planet's mass 1,760° Fahrenheit, but that the distribution of this heat-generation has been such as not to interfere with the normal augmentation of temperature downward due to secular cooling, and the conclusion drawn therefrom by Sir William Thomson. Mr. Darwin further concludes from his hypothesis that the ellipticity of the earth's figure having been continually diminishing, "the polar regions must have been ever rising and the equatorial ones falling, though as the ocean followed these changes, they might quite well have left no geological traces. The tides must have been very much more frequent and larger, and accordingly the rate of oceanic denudation much accelerated. The more rapid alternation of day and night[1] would probably lead to more sudden and violent storms, and the increased rotation of the earth would augment the violence of the trade-winds, which in their turn would affect oceanic currents."[2] As above stated, no facts yet revealed by the geological record compel the admission of more violent superficial action in former times than now. But though the facts do not of themselves lead to such an admission, it is proper to enquire whether any of them are hostile to it. It will be shown in Book VI. that even as far back as early Palæozoic times, that is, as far into the past as the history of organised life can be traced, sedimentation took place very much as it does now. Sheets of fine mud and silt were pitted with rain drops, ribbed with ripple-marks, and furrowed by crawling worms, exactly as they now are on the shores of any modern estuary. These surfaces were quietly buried under

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[1] The student ought, however, to consult Prof. Suess' *Antlitz der Erde* for the arguments in favour of an opposite opinion.

[2] *Nature*, xvi. (1877), p. 415.

[3] *Phil. Trans.* 1879, parts i. and ii.

[4] The degree of viscosity assumed is such that "thirteen and a half tons to the square inch acting for twenty-four hours on a slab an inch thick displaces the upper

surface relatively to the lower through one-tenth of an inch. It is obvious," says Mr. Darwin, "that such a substance as this would be called a solid in ordinary parlance, and in the tidal problem this must be regarded as a very small viscosity." *Op. cit.* p. 531.

[1] According to his calculation, the year 57,000,000 of years ago contained 1300 days instead of 365.

[2] *Op. cit.* p. 532.

succeeding sediment of a similar kind, and this for hundreds and thousands of feet. Nothing indicates violence; all the evidence favours tranquil deposit.[1] If, therefore, Mr. Darwin's hypothesis be accepted, we must conclude either that it does not necessarily involve such violent superficial operations as he supposes, or that even the oldest sedimentary formations do not date back to a time when the influence of increased rotation could make itself evident in sedimentation, that is to say, on Mr. Darwin's hypothesis, the most ancient fossiliferous rocks cannot be as much as 57,000,000 years old.

§ 8. **Climate in its Geological Relations.**—In subsequent parts of this volume data will be given from which we learn that the climates of the earth have formerly been considerably different from those which at present prevail. A consideration of the history of the solar system would of itself suggest the inference that, on the whole, the climates of early geological periods must have been warmer. The sun's heat was greater, probably the amount of it received by the earth was likewise greater, while there would be for some time a sensible influence of the planet's own internal heat upon the general temperature of the whole globe.[2] Although arguments based upon the probable climatal necessities of extinct species and genera of plants and animals must be used with extreme caution, it may be asserted with some confidence that from the vast areas over which Palæozoic mollusks have been traced, alike in the eastern and the western hemispheres, the climates of the globe in Palæozoic time were probably more uniform than they now are. There appears to have been a gradual lowering of the general temperature during past geological time, accompanied by a tendency towards greater extremes of climate. But there are proofs also that at longer or shorter intervals cold cycles have intervened. The Glacial Period, for example, preceded our own time, and in successive geological formations indications, of more or less value, have been found that suggest if they do not prove a former prevalence of ice in what are now temperate regions.[3]

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[1] Sir R. Ball (*Nature*, xxv. 1881, pp. 79, 103), starting from Professor Darwin's data, pushed his conclusions to such an extreme as to call in the agency of tides more than 600 feet high in early geological times. In repudiating this application of his results, Mr. Darwin (*Nature*, xxv. p. 213) employs the argument I have here used from the absence of any evidence of such tidal action in the geological formations, and from the indication, on the contrary, of tranquil deposit.

[2] Lord Kelvin (Sir William Thomson) believes that the hypothesis that terrestrial temperature was formerly higher by reason of a hotter sun "is rendered almost infinitely probable by independent physical evidence and mathematical calculation." (*Trans. Geol. Soc. Glasgow*, v. p. 238.) Professor Tait, however, has suggested, that the former greater heat of the sun may have raised such vast clouds of absorbing vapour round that luminary as to prevent the effective amount of radiation of heat to the earth's surface from being greater than at present; while on the other hand, a similar supposition may be made with reference to the greater amount of vapour which increased solar radiation would raise to be condensed in the earth's atmosphere. 'Recent Advances in Physical Science,' 1876, p. 174.

[3] Consult a suggestive paper by the late Dr. M. Neumayr, *Nature*, xlii. (1890), p. 148.

Various theories have been proposed in explanation of such alternations of climate. Some of these have appealed to a change in the position of the earth's axis relatively to the mass of the planet (*ante*, § 5). Others have been based on the notion that the earth may have passed through hot and cold regions of space. Others, again, have called in the effects of terrestrial changes, such as the distribution of land and sea, on the assumption that elevation of land about the poles must cool the temperature of the globe, while elevation round the equator would raise it.[1] But the changes of temperature appear to have affected the whole of the earth's surface, while there is not only no proof of any such enormous vicissitudes in physical geography as would be required, but good grounds for believing that the present terrestrial and oceanic areas have remained, on the whole, on the same sites from very early geological time. Moreover, as evidence has accumulated in favour of periodic alternations of climate, the conviction has been strengthened that no mere local changes could have sufficed, but that secular variations in climate must be assigned to some general and probably recurring cause.

By degrees, geologists accustomed themselves to the belief that the cold of the Glacial Period was not due to mere terrestrial changes, but was to be explained somehow as the result of cosmical causes. Of various suggestions as to the probable nature and operation of these causes, one deserves careful consideration—change in the eccentricity of the earth's orbit. Sir John Herschel[2] pointed out many years ago that the direct effect of a high condition of eccentricity is to produce an unusually cold winter, followed by a correspondingly hot summer, in the hemisphere whose winter occurs in aphelion, while an equable condition of climate at the same time prevails on the opposite hemisphere. But both hemispheres must receive precisely the same amount of solar heat, because the deficiency of heat, resulting from the sun's greater distance during one part of the year, is exactly compensated by the greater length of that season. Sir John Herschel even considered that the direct effects of eccentricity must thus be nearly neutralised.[3] As a like verdict was afterwards given by Arago, Humboldt, and others, geologists were satisfied that no important change of climate could be attributed to change of eccentricity.

The late Dr. James Croll, as far back as the year 1864, made an important suggestion in this matter, and subsequently worked out an elaborate development of the whole subject of the physical causes on which climate depends.[4] He was good enough to draw up the following abstract of them for former editions of the present work.

"Assuming the mean distance of the sun to be 92,400,000 miles, then when the eccentricity is at its superior limit, ·07775, the distance of the sun from the earth, when the latter is in the aphelion of its orbit, is no less than 99,584,100 miles, and when in the perihelion it is only 85,215,900 miles. The earth is, therefore, 14,368,200 miles farther from the sun in the former than in the latter position. The direct heat of the sun being inversely as the square of the distance, it follows that the amount of heat received by the earth in these two positions will be as 19 to 26. The present eccentricity being ·0168, the earth's distance during our northern winter is 90,847,680 miles. Suppose now that, from the precession of the equinoxes, winter in our northern hemisphere should happen when the earth is in the aphelion of its orbit, at the time that the orbit is at its greatest eccentricity; the earth would then be 8,736,420 miles farther from the sun in winter than it is at present. The direct heat of the sun would therefore, during winter, be one-fifth less and during summer one-fifth greater than now.

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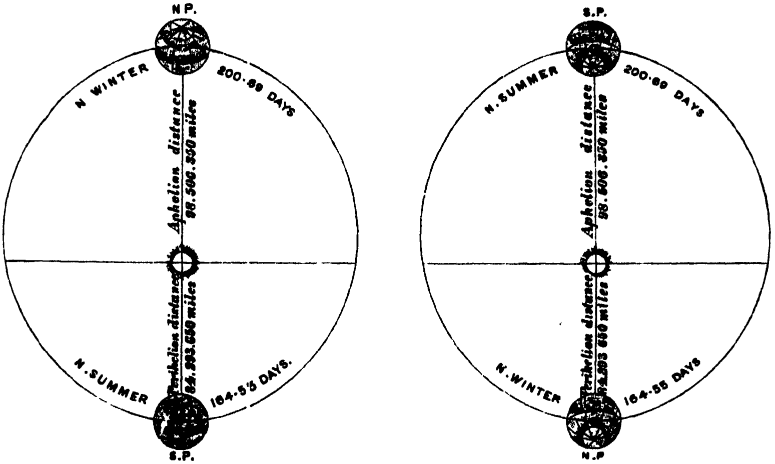
[1] In Lyell's 'Principles of Geology,' this doctrine of the influence of geographical changes is maintained.

[2] *Trans. Geol. Soc.* vol. iii. p. 293 (2nd series).

[3] 'Cabinet Cyclopædia,' sec. 315; 'Outlines of Astronomy,' sec. 368.

[4] *Phil. Mag.* xxviii. (1864), p. 121. His researches will be found in detail in his volume 'Climate and Time,' 1875, and his later work 'Discussions on Climate and Cosmology.'



N. Winter Solstice in Aphelion. *N. Winter Solstice in Perihelion.*

Fig. 1.—Eccentricity of the Earth's Orbit in Relation to Climate.

This enormous difference would necessarily affect the climate to a very great extent. Were the winters under these circumstances to occur when the earth was in the perihelion of its orbit, the earth would then be 14,368,200 miles nearer the sun in winter than in summer. In this case the difference between winter and summer in our latitudes would be almost annihilated. But as the winters in the one hemisphere correspond with the summers in the other, it follows that while the one hemisphere would be enduring the greatest extremes of summer heat and winter cold, the other would be enjoying perpetual summer.

"It is quite true that, whatever may be the eccentricity of the earth's orbit, the two hemispheres must receive equal quantities of heat per annum; for proximity to the sun is exactly compensated by the effect of swifter motion. The total amount of heat received from the sun between the two equinoxes is, therefore, the same in both halves of the year, whatever the eccentricity of the earth's orbit may be. For example, whatever extra heat the southern hemisphere may at present receive per day from the sun during its summer months, owing to greater proximity to the sun, is exactly compensated by a corresponding loss arising from the shortness of the season; and, on the other hand, whatever deficiency of heat we in the northern hemisphere may at present have per day during our summer half-year, in consequence of the earth's distance from the sun, is also exactly compensated by a corresponding length of season.

"It is well known, however, that those simple changes in the summer and winter

Various theories have been proposed in explanation of such alternations of climate. Some of these have appealed to a change in the position of the earth's axis relatively to the mass of the planet (*ante*, § 5). Others have been based on the notion that the earth may have passed through hot and cold regions of space. Others, again, have called in the effects of terrestrial changes, such as the distribution of land and sea, on the assumption that elevation of land about the poles must cool the temperature of the globe, while elevation round the equator would raise it.[1] But the changes of temperature appear to have affected the whole of the earth's surface, while there is not only no proof of any such enormous vicissitudes in physical geography as would be required, but good grounds for believing that the present terrestrial and oceanic areas have remained, on the whole, on the same sites from very early geological time. Moreover, as evidence has accumulated in favour of periodic alternations of climate, the conviction has been strengthened that no mere local changes could have sufficed, but that secular variations in climate must be assigned to some general and probably recurring cause.

By degrees, geologists accustomed themselves to the belief that the cold of the Glacial Period was not due to mere terrestrial changes, but was to be explained somehow as the result of cosmical causes. Of various suggestions as to the probable nature and operation of these causes, one deserves careful consideration—change in the eccentricity of the earth's orbit. Sir John Herschel[2] pointed out many years ago that the direct effect of a high condition of eccentricity is to produce an unusually cold winter, followed by a correspondingly hot summer, in the hemisphere whose winter occurs in aphelion, while an equable condition of climate at the same time prevails on the opposite hemisphere. But both hemispheres must receive precisely the same amount of solar heat, because the deficiency of heat, resulting from the sun's greater distance during one part of the year, is exactly compensated by the greater length of that season. Sir John Herschel even considered that the direct effects of eccentricity must thus be nearly neutralised.[3] As a like verdict was afterwards given by Arago, Humboldt, and others, geologists were satisfied that no important change of climate could be attributed to change of eccentricity.

The late Dr. James Croll, as far back as the year 1864, made an important suggestion in this matter, and subsequently worked out an elaborate development of the whole subject of the physical causes on which climate depends.[4] He was good enough to draw up the following abstract of them for former editions of the present work.

"Assuming the mean distance of the sun to be 92,400,000 miles, then when the eccentricity is at its superior limit, ·07775, the distance of the sun from the earth, when the latter is in the aphelion of its orbit, is no less than 99,584,100 miles, and when in the perihelion it is only 85,215,900 miles. The earth is, therefore, 14,368,200 miles farther from the sun in the former than in the latter position. The direct heat of the sun being inversely as the square of the distance, it follows that the amount of heat received by the earth in these two positions will be as 19 to 26. The present eccentricity being ·0168, the earth's distance during our northern winter is 90,847,680 miles. Suppose now that, from the precession of the equinoxes, winter in our northern hemisphere should happen when the earth is in the aphelion of its orbit, at the time that the orbit is at its greatest eccentricity; the earth would then be 8,736,420 miles farther from the sun in winter than it is at present. The direct heat of the sun would therefore, during winter, be one-fifth less and during summer one-fifth greater than now.

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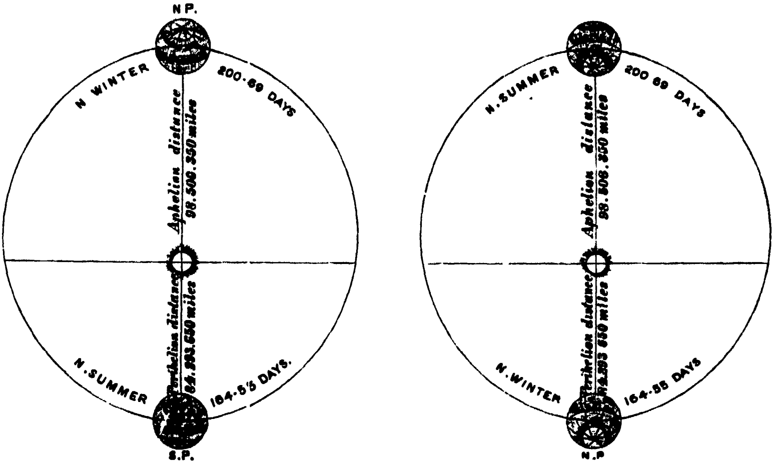
[1] In Lyell's 'Principles of Geology,' this doctrine of the influence of geographical changes is maintained.

[2] *Trans. Geol. Soc.* vol. iii. p. 293 (2nd series).

[3] 'Cabinet Cyclopædia,' sec. 315; 'Outlines of Astronomy,' sec. 368.

[4] *Phil. Mag.* xxviii. (1864), p. 121. His researches will be found in detail in his volume 'Climate and Time,' 1875, and his later work 'Discussions on Climate and Cosmology.'



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This enormous difference would necessarily affect the climate to a very great extent. Were the winters under these circumstances to occur when the earth was in the perihelion of its orbit, the earth would then be 14,368,200 miles nearer the sun in winter than in summer. In this case the difference between winter and summer in our latitudes would be almost annihilated. But as the winters in the one hemisphere correspond with the summers in the other, it follows that while the one hemisphere would be enduring the greatest extremes of summer heat and winter cold, the other would be enjoying perpetual summer.

"It is quite true that, whatever may be the eccentricity of the earth's orbit, the two hemispheres must receive equal quantities of heat per annum; for proximity to the sun is exactly compensated by the effect of swifter motion. The total amount of heat received from the sun between the two equinoxes is, therefore, the same in both halves of the year, whatever the eccentricity of the earth's orbit may be. For example, whatever extra heat the southern hemisphere may at present receive per day from the sun during its summer months, owing to greater proximity to the sun, is exactly compensated by a corresponding loss arising from the shortness of the season; and, on the other hand, whatever deficiency of heat we in the northern hemisphere may at present have per day during our summer half-year, in consequence of the earth's distance from the sun, is also exactly compensated by a corresponding length of season.

"It is well known, however, that those simple changes in the summer and winter distances would not alone produce a glacial epoch, and that physicists, confining their attention to the purely astronomical effects, were perfectly correct in affirming that no increase of eccentricity of the earth's orbit could account for that epoch. But the important fact was overlooked that, although the glacial epoch could not result directly from an increase of eccentricity, it might nevertheless do so indirectly from physical agents that were brought into operation as a result of an increase of eccentricity. The following is an outline of what these physical agents were, how they were brought into operation, and the way in which they may have led to the glacial epoch.

"With the eccentricity at its superior limit and the winter occurring in the aphelion, the earth would, as we have seen, be 8,736,420 miles farther from the sun during that season than at present. The reduction in the amount of heat received from the sun owing to his increased distance, would lower the midwinter temperature to an enormous extent. In temperate regions the greater portion of the moisture of the air is at present precipitated in the form of rain, and the very small portion which falls as snow disappears in the course of a few weeks at most. But in the circumstances under consideration, the mean winter-temperature would be lowered so much below the freezing-point that what now falls as rain during that season, would then fall as snow. This is not all; the winters would then not only be cooler than now, but they would also be much longer. At present the winters are nearly eight days shorter than the summers; but with the eccentricity at its superior limit and the winter solstice in aphelion, the length of the winters would exceed that of the summers by no fewer than thirty-six days. The lowering of the temperature and the lengthening of the winter would both tend to the same effect, viz., to increase the amount of snow accumulated during the winter; for, other things being equal, the longer the snow-accumulating period the greater the accumulation. It may be remarked, however, that the absolute quantity of heat received during winter is not affected by the decrease in the sun's heat, for the additional length of the season compensated for this decrease.[1] As regards the absolute amount of heat received, increase of the sun's distance and lengthening of the winter are compensatory, but not so in regard to the amount of snow accumulated. The consequence of this state of things would be that, at the commencement of the short summer, the ground would be covered with the winter's accumulation of snow. Again, the presence of so much snow would lower the summer temperature, and prevent to a great extent the melting of the snow.

"There are three separate ways whereby accumulated masses of snow and ice tend to lower the summer temperature, viz.:—

"*First*, By means of direct radiation. No matter what the intensity of the sun's rays may be, the temperature of snow and ice can never rise above 32°. Hence, the presence of snow and ice tends by direct radiation to lower the temperature of all surrounding bodies to 32°. In Greenland, a country covered with snow and ice, the pitch has been seen to melt on the side of a ship exposed to the direct rays of the sun, while at the same time, the surrounding air was far below the freezing-point; a thermometer exposed to the direct radiation of the sun has been observed to stand above 100°, while the air surrounding the instrument was actually 12° below the freezing-point. A similar experience has been recorded by travellers on the snow-fields of the Alps. These results, surprising as they no doubt appear, are what we ought to expect under the circumstances. Perfectly dry air seems to be nearly incapable of absorbing radiant heat. The entire radiation passes through it almost without any sensible absorption. Consequently the pitch on the side of the ship may be melted, or the bulb of the thermometer raised to a high temperature by the direct rays of the sun, while the surrounding air remains intensely cold. The air is cooled by *contact* with the snow-covered ground, but is not heated by the radiation from the sun.

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[1] When the eccentricity is at its superior limit, the absolute quantity of heat received by the earth during the year is, however, about one three-hundredth part greater than at present. But this does not affect the question at issue.

"When the air is charged with aqueous vapour, a similar cooling effect also takes place, but in a slightly different way. Air charged with aqueous vapour is a good absorber of radiant heat, but it can only absorb those rays which agree with it in *period*. It so happens that rays from snow and ice are, of all others, those which it absorbs best. The humid air will absorb the total radiation from the snow and ice, but it will allow the greater part of, if not nearly all, the sun's rays to pass unabsorbed. But during the day, when the sun is shining, the radiation from the snow and ice to the air is negative; that is, the snow and ice cool the air by radiation. The result is, the air is cooled by radiation from the snow and ice (or rather, we should say, *to* the snow and ice) more rapidly than it is heated by the sun; and as a consequence, in a country like Greenland, covered with an icy mantle, the temperature of the air, even during summer, seldom rises above the freezing-point. Snow is a good reflector, but as simple reflection does not change the character of the rays, they would not be absorbed by the air, but would pass into stellar space. Were it not for the ice, the summers of North Greenland, owing to the continuance of the sun above the horizon, would be as warm as those of England; but instead of this, the Greenland summers are colder than our winters. Cover India with an ice sheet, and its summers would be colder than those of England.

"*Second*, Another cause of the cooling effect is that the rays which fall on snow and ice are to a great extent reflected back into space. But those that are not reflected, but absorbed, do not raise the temperature, for they disappear in the mechanical work of melting the ice. For whatsoever may be the intensity of the sun's heat, the surface of the ground will be kept at 32° so long as the snow and ice remain unmelted.

Third, Snow and ice lower the temperature by chilling the air and condensing the vapour into thick fogs. The great strength of the sun's rays during summer, due to his nearness at that season, would, in the first place, tend to produce an increased amount of evaporation. But the presence of snow-clad mountains and an icy sea would chill the atmosphere and condense the vapour into thick fogs. The thick fogs and cloudy sky would effectually prevent the sun's rays from reaching the earth, and the snow, in consequence, would remain unmelted during the entire summer. In fact, we have this very condition of things exemplified in some of the islands of the Southern Ocean at the present day. Sandwich Land, which is in the same parallel of latitude as the north of Scotland, is covered with ice and snow the entire summer; and in the island of South Georgia, which is in the same parallel as the centre of England, the perpetual snow descends to the very sea-beach. Captain Sir James Ross found the perpetual snow at the sea-level at Admiralty Inlet, South Shetland, in lat. 64°; and while near this place the thermometer in the very middle of summer fell at night to 23° F. The reduction of the sun's heat and lengthening of the winter, which would take place when the eccentricity is near to its superior limit and the winter in aphelion, would in this country produce a state of things perhaps as bad as, if not worse than, that which at present exists in South Georgia and South Shetland.

"The cause which above all others must tend to produce great changes of climate, is the deflection of great ocean currents. A high condition of eccentricity tends, we have seen, to produce an accumulation of snow and ice on the hemisphere whose winters occur in aphelion. The accumulation of snow, in turn, tends to lower the summer temperature, cut off the sun's rays, and retard the melting of the snow. In short, it tends to produce, on that hemisphere, a state of glaciation. Exactly opposite effects take place on the other hemisphere, which has its winter in perihelion. There the shortness of the winters, combined with the high temperature arising from the nearness of the sun, tends to prevent the accumulation of snow. The general result is that the one hemisphere is cooled and the other heated. This state of things now brings into play the agencies which lead to the deflection of the Gulf-stream and other great ocean currents.

"Owing to the great difference between the temperature of the equator and the poles, there is a constant flow of air from the poles to the equator. It is to this that the trade-winds owe their existence. Now, as the strength of these winds will, as a general rule, depend upon the difference of temperature that may exist between the equator and higher latitudes, it follows that the trades on the cold hemisphere will be stronger than those on the warm. When the polar and temperate regions of the one hemisphere are covered to a large extent with snow and ice, the air, as we have just seen, is kept almost at the freezing-point during both summer and winter. The trades on that hemisphere will, of necessity, be exceedingly powerful; while on the other hemisphere, where there is comparatively little snow or ice, and the air is warm, the trades will consequently be weak. Suppose now the northern hemisphere to be the cold one. The north-east trade-winds of this hemisphere will far exceed in strength the south-east trade-winds of the southern hemisphere. The *median line* between the trades will consequently lie to a very considerable distance to the south of the equator. We have a good example of this at the present day. The difference of temperature between the two hemispheres at present is but trifling to what it would be in the case under consideration; yet we find that the south-east trades of the Atlantic blow with greater force than the north-east trades, sometimes extending to 10° or 15° N. lat., whereas the north-east trades seldom blow south of the equator. The effect of the northern trades blowing across the equator to a great distance will be to impel the warm water of the tropics over into the Southern Ocean. But this is not all; not only would the median line of the trades be shifted southwards, but the great equatorial currents of the globe would also be shifted southwards.

"Let us now consider how this would affect the Gulf-stream. The South American continent is shaped somewhat in the form of a triangle, with one of its angular corners, called Cape St. Roque, pointing eastwards. The equatorial current of the Atlantic impinges against this corner; but as the greater portion of the current lies a little to the north of the corner, it flows westward into the Gulf of Mexico and forms the Gulf-stream. A considerable portion of the water, however, strikes the land to the south of the cape, and is deflected along the shore of Brazil into the Southern Ocean, forming what is known as the Brazilian current. Now, it is obvious that the shifting of the equatorial current of the Atlantic only a few degrees to the south of its present position—a thing which would certainly take place under the conditions which we have been detailing—would turn the entire current into the Brazilian branch, and instead of flowing chiefly into the Gulf of Mexico, as at present, it would all flow into the Southern Ocean, and the Gulf-stream would consequently be stopped. The stoppage of the Gulf-stream, combined with all those causes which we have just been considering, would place Europe under a glacial condition, while at the same time the temperature of the Southern Ocean would, in consequence of the enormous quantity of warm water received, have its temperature (already high from other causes) raised enormously. And what holds true in regard to the currents of the Atlantic holds also true, though perhaps not to the same extent, of the currents of the Pacific.

"If the breadth of the Gulf-stream be taken at 50 miles, its depth at 1000 feet, its mean velocity at 2 statute miles an hour, the temperature of the water when it leaves the Gulf at 65°, and the return current at 40° F.,[1] then, the quantity of heat conveyed into the Atlantic by this stream is equal to one-fourth of all the heat received from the sun by that ocean from the Tropic of Cancer to the Arctic Circle.[2] From principles discussed at considerable length in 'Climate and Time' it is shown that, but for the Gulf-stream and other currents, London would have a mean annual temperature 40° lower than at present.

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[1] Sir Wyville Thomson states that in May, 1873, the *Challenger* expedition found the Gulf-stream, at the point where it was crossed, to be about sixty miles in width, 100 fathoms deep, and flowing at the rate of three knots per hour. This makes the volume of the stream one-fifth greater than the above estimate.

[2] The quantity of heat conveyed by the Gulf-stream for distribution is equal to 77,479,650,000,000,000,000 foot-pounds per day. The quantity received from the sun by the North Atlantic is 310,923,000,000,000,000,000 foot-pounds. 'Climate and Time,' chap. ii.

"But there is still another cause which must be noticed:—a strong undercurrent of air *from* the north implies an equally strong upper current *to* the north. Now if the effect of the undercurrent would be to impel the warm water at the equator to the south, the effect of the upper current would be to carry the aqueous vapour formed at the equator to the north; the upper current, on reaching the snow and ice of temperate regions, would deposit its moisture in the form of snow; so that it is probable that, notwithstanding the great cold of the glacial epoch, the quantity of snow falling in the northern regions would be enormous. This would be particularly the case during summer, when the earth would be in the perihelion and the heat at the equator great. The equator would be the furnace where evaporation would take place, and the snow and ice of temperate regions would act as a condenser.

"The foregoing considerations, as well as many others which might be stated, lead to the conclusion that, in order to raise the mean temperature of the globe, *water* should be placed along the equator, and not *land*, as was contended by Sir Charles Lyell and others. For if land be placed at the equator, the possibility of conveying the sun's heat from the equatorial regions by means of ocean currents is prevented."[1]

The astronomical theory in explanation of former great differences of terrestrial climate has recently been illustrated and enforced by Sir Robert Ball, who, while strengthening the general arguments in its favour, especially insists upon the existence of an important law in the distribution of solar heat on the earth's surface, which he thinks has been hitherto overlooked. He remarks that the original statement of Sir John Herschel that the heat received by the earth from the sun is equally divided between the winter and summer seasons has given rise to an entirely erroneous impression. Although "it is certainly true that during the summer in one hemisphere the heat received on the whole earth is equal to the heat received on the whole earth during the ensuing winter on the same hemisphere," yet on any given hemisphere almost twice as much heat can be demonstrated to be received during summer as during winter.[2] The law is thus stated: "Of the total amount of heat received from the sun on a hemisphere of the earth in the course of a year, 63 per cent is received during the summer, and 37 per cent is received during the winter."[3] It is obvious that while, under the operation of this law, the total amount of heat received and the ratio of its distribution between summer and winter would remain unchanged, enormous differences in terrestrial climate might result according as the seasons varied in length with changes in the eccentricity of the orbit.

Inter-Glacial Periods.—Allusion has already been made to the accumulating evidence that changes of climate have been recurrent, and to the deduction from this alternation or periodicity that they have probably been due to some general or cosmical cause. Dr. Croll ingeniously showed that every long cold period arising in each hemisphere from the circumstances sketched in the preceding pages, must have been interrupted by several shorter warm periods.

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[1] That climate, however, may be considerably affected by changes, such as are known to have taken place in the distribution of land and sea, must be frankly conceded. This has been recently cogently argued by Mr. Wallace in his 'Island Life,' 1880. Mr. Croll's views, summarised above, have been adversely criticised by Prof. Newcombe, for whose papers and Dr. Croll's replies see *Amer. Journ. Science*, 1876, 1883, 1884, and the work by the latter writer, 'Discussions on Climate and Cosmology,' already referred to.

[2] 'The Cause of an Ice Age,' London, 1891, p. 120. [3] *Ibid.* p. 90.

"When the one hemisphere," he says, "is under glaciation, the other is enjoying a warm and equable climate. But, owing to the precession of the equinoxes, the condition of things on the two hemispheres must be reversed every 10,000 years or so. When the solstice passes the aphelion, a contrary process commences ; the snow and ice gradually begin to diminish on the cold hemisphere and to make their appearance on the other hemisphere. The glaciated hemisphere turns by degrees warmer, and the warm hemisphere colder, and this continues to go on for a period of ten or twelve thousand years, until the winter solstice reaches the perihelion. By this time the conditions of the two hemispheres have been reversed ; the formerly glaciated hemisphere has now become the warm one, and the warm hemisphere the glaciated. The transference of the ice from the one hemisphere to the other continues as long as the eccentricity remains at a high value. It is probable that, during the warm inter-glacial periods, Greenland and the Arctic regions would be comparatively free from snow and ice, and enjoying a temperate and equable climate."

BOOK II.

GEOGNOSY.

AN INVESTIGATION OF THE MATERIALS OF THE EARTH'S SUBSTANCE.

PART I.—A GENERAL DESCRIPTION OF THE PARTS OF THE EARTH.

A DISCUSSION of the geological changes which our planet has undergone, ought to be preceded by a study of the materials of which the planet consists. This latter branch of inquiry is termed Geognosy.

Viewed in a broad way, the earth may be considered as consisting of (1) two envelopes,—an outer one of gas (atmosphere), completely surrounding the planet, and an inner one of water (hydrosphere), covering about three-fourths of the globe; and (2) a globe (lithosphere), cool and solid on its surface, but possessing a high internal temperature.

I.—*The Envelopes—Atmosphere and Hydrosphere.*

It is certain that the present gaseous and liquid envelopes of the planet form only a portion of the original mass of gas and water with which the globe was invested. Fully a half of the outer shell or crust of the earth consists of oxygen, which, there can be no doubt, once existed in the atmosphere. The extent, likewise, to which water has been abstracted by minerals is almost incredible. It has been estimated that already one-third of the whole mass of the ocean has been thus absorbed. Eventually the condition of the planet will probably resemble that of the moon—a globe without air, or water, or life of any kind.

1. **The Atmosphere.**—The gaseous envelope to which the name of atmosphere is given, extends to a distance of perhaps 500 or 600 miles from the earth's surface, possibly in a state of extreme tenuity to a still greater height. But its thickness must necessarily vary with latitude and changes in atmospheric pressure. The layer of air lying over the poles is not so deep as that which surrounds the equator.

Many speculations have been made regarding the chemical composition of the atmosphere during former geological periods. There can indeed be no doubt that it must originally have differed very greatly from its present condition. Besides the abstraction of the oxygen which now forms fully a half of the outer crust of the earth, the vast beds of coal found all over the world, in geological formations of many different ages, doubtless represent so much carbon-dioxide (carbonic acid) once present in the air. According to Sterry Hunt, the amount of carbonic acid absorbed in the process of rock-decay, and now represented in the form of carbonates in the earth's crust, probably equals two hundred times the present volume of the entire atmosphere.[1] The chlorides in the sea, likewise, were probably carried down out of the atmosphere in the primitive condensation of aqueous vapour. It has often been stated that, during the Carboniferous period, the atmosphere must have been warmer and with more aqueous vapour and carbon-dioxide in its composition than at the present day, to admit of so luxuriant a flora as that from which the coal-seams were formed. There seems, however, to be at present no method of arriving at any certainty on this subject.

As now existing, the atmosphere is considered to be normally a mechanical mixture of nearly 4 volumes of nitrogen and 1 of oxygen (N79·4, O20·6), with minute proportions of carbon-dioxide and water-vapour and still smaller quantities of ammonia and the powerful oxidising agent, ozone. These quantities are liable to some variation according to locality. The mean proportion of carbon-dioxide is about 3·5 parts in every 10,000 of air. In the air of streets and houses the proportion of oxygen diminishes, while that of carbon-dioxide increases. According to the researches of Angus Smith, very pure air should contain not less than 20·99 per cent. of oxygen, with 0·030 of carbon-dioxide; but he found impure air in Manchester to have only 20·21 of oxygen, while the proportion of carbon-dioxide in that city during fog was ascertained to rise sometimes to 0·0679, and in the pit of the theatre to the very large amount of 0·2734. As plants absorb carbon-dioxide during the day and give it off at night, the quantity of this gas in the atmosphere oscillates between a maximum at night and a minimum during the day. During the part of the year when vegetation is active, it is believed that there is at least 10 per cent. more carbonic acid in the air of the open country at night than in the day.[2] Small as the normal percentage of this gas in the air may seem, yet the total amount of it in the whole atmosphere probably exceeds what would be disengaged if all the vegetable and animal matter on the earth's surface were burnt.

The other substances in the air are gases, vapours, and solid particles. Of these by much the most important is the vapour of water, which is always present, but in very variable amount according to temperature.[3]

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[1] *Brit. Assoc. Rep.* 1878, Sects. p. 544.

[2] Prof. G. F. Armstrong. *Proc. Roy. Soc.* xxx. (1880), p. 343.

[3] A cubic metre of air at the freezing-point can hold only 4·871 grammes of water-vapour, but at 40° C. can take up 50·70 grammes. One cubic mile of air saturated with vapour at 35° C. will, if cooled to 0°, deposit upwards of 140,000 tons of water as rain. Roscoe and Schorlemmer's 'Chemistry,' i. p. 452.

It is this vapour which chiefly absorbs radiant heat.[1] It condenses into dew, rain, hail, and snow. In assuming a visible form, and descending through the atmosphere, it takes up a minute quantity of air, and of the different substances which the air may contain. Being caught by the rain, and held in solution or suspension, these substances can be best examined by analysing rain-water. In this way, the atmospheric gases, ammonia, nitric, sulphurous, and sulphuric acids, chlorides, various salts, solid carbon, inorganic dust, and organic matter have been detected. The fine microscopic dust so abundant in the air is no doubt for the most part due to the action of wind in lifting up the finer particles of disintegrated rock on the surface of the land. Volcanic explosions sometimes supply prodigious quantities of fine dust. There is probably also some addition to the solid particles in the atmosphere from the explosion and dissipation of meteorites on entering our atmosphere. To the wide diffusion of minute solid particles in the air great importance in the condensation of vapour has recently been assigned. (Book III. Part II. Section ii.)

The comparatively small, but by no means unimportant, proportions of these minor components of the atmosphere are much more liable to variation than those of the more essential gases. Chloride of sodium, for instance, is, as might be expected, particularly abundant in the air bordering the sea. Nitric acid, ammonia, and sulphuric acid appear most conspicuously in the air of towns. The organic substances present in the air are sometimes living germs, such as probably often lead to the propagation of disease, and sometimes mere fine particles of dust derived from the bodies of living or dead organisms.[2]

As a geological agent, the atmosphere effects changes by the chemical reactions of its constituent gases and vapours, by its varying temperature, and by its motions. Its functions in these respects are described in Book III. Part II. Section i.

2. **The Oceans.**—Rather less than three-fourths of the surface of the globe (or about 144,712,000 square miles) are covered by the irregular sheet of water known as the Sea. Within the last twenty years, much new light has been thrown upon the depths, temperatures, and biological conditions of the ocean-basins, more particularly by the *Lightning*, *Porcupine*, *Challenger*, *Tuscarora*, *Blake*, *Gazelle* and other expeditions fitted out by the British, American, German, and Norwegian Governments.[3] It

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[1] See Tyndall's researches which established this important function of the aqueous vapour of the atmosphere, and their confirmation by meteorological observation. S. A. Hill, *Proc. Roy. Soc.* xxxiii. 216, 435.

[2] The air of towns is peculiarly rich in impurities, especially in manufacturing districts, where much coal is used. These impurities, however, though of serious consequence to the towns in a sanitary point of view, do not sensibly affect the general atmosphere, seeing that they are probably in great measure taken out of the air by rain, even in the districts which produce them. They possess, nevertheless, a special geological significance, and in this respect, too, have important economic bearings. See on this whole subject, Angus Smith's 'Air and Rain,' and the account of Rain in Book III. Part II. Sect. ii.

[3] See Wyville Thomson, 'The Depths of the Sea,' 1873; 'The Atlantic,' 1877; 'Report of *Challenger* Expedition,' especially the forthcoming volumes giving a summary of results; A. Agassiz, 'Three Cruises of the *Blake*,' 1888; 'Den Norske Nordhavs-Expedition,' 1876-1878.

has been ascertained that few parts of the Atlantic Ocean exceed 3000 fathoms, the deepest sounding obtained there being one taken about 100 miles north from the island of St. Thomas, which gave 3875 fathoms, or rather less than 4½ miles. The Atlantic appears to have an average depth in its more open parts of from 2000 to 3000 fathoms, or from about 2 to 3½ miles. In the Pacific Ocean H.M. Ship *Challenger* got soundings of 3950 and 4475 fathoms, or about 4½ and rather more than 5 miles. Since then the U.S. Ship *Tuscarora* obtained a still deeper sounding (4655 fathoms), to the east of the Kurile Islands. This is the deepest abyss yet found in any part of the ocean. But these appear to mark exceptionally abysmal depressions, the average depth being, as in the Atlantic, between 2000 and 3000 fathoms. We may therefore assume, as probably not far from the truth, that the average depth of the sea is about 2500 fathoms, or nearly 3 miles. Its total cubic contents will thus be about 400 millions of cubic miles.

With regard also to the form of the bottom of the great oceans, much additional information has recently been obtained. Over vast areas in the central regions, the sea-floor appears to form great plains, with comparatively few inequalities, but with lines of submarine ridges, comparable to chains of hills or mountains on the land. Recent soundings, however, taken at short distances, have revealed, in parts of the Atlantic that were supposed to be deep and with a tolerably uniform bottom, submarine peaks rising to within 50 fathoms from the surface.[1] A vast central ridge has also been traced down the length of this ocean, from which a few lonely peaks rise above sea-level—the Azores, St. Paul, Ascension, and Tristan d'Acunha. In the Pacific Ocean, the lines of coral-islands appear to rise on submarine ridges, having a general north-westerly and south-easterly trend. It is significant that the islands which thus appear far from any large mass of land are either coral-reefs or of volcanic origin, and contain none of the granites, schists and other ordinary continental rocks. St. Helena and Ascension in the Atlantic, and the Friendly and Sandwich Islands in the Pacific Ocean are conspicuous examples.

Another important result of recent deep-sea research is the determination of the relation of mediterranean seas to the main ocean. These basins, such as the North, Mediterranean, and Black Seas, the Gulf of Mexico, Caribbean Sea, Baffin's Bay, Hudson's Bay, Sea of Okhotsk, and Chinese Sea, belong rather to the continental than the oceanic areas of the earth's surface. An elevation of a few hundred fathoms would convert most of them into land, with here and there deep water-filled basins.

A question of high importance in geological enquiry is the form of the surface of the sea or what is usually called the sea-level. It has been generally assumed that this surface is stable and uniform and nearly that of an ellipsoid of revolution, owing its equilibrium to the force of gravity on the one hand and the centrifugal force of rotation on the other. But in recent years this conception has been called in question both by physicists and geologists. Observations as well as calculations have shown that the attraction exercised by masses of land raises the level of the adjacent sea, and attempts have been made to determine how far the deformation thus caused departs from the mean of the theoretical ellipsoid of revolution. According to Bruns a continent may cause a difference of more than 3000 feet between the actual level of the sea and that of the ellipsoid. But the results of such calculations will greatly depend on the assumption on which they start as to the nature of the earth's crust. R. S. Woodward has calculated that if the continent of Europe and Asia be supposed to be simply a superficial aggregation of matter with a density as great as the parts under the sea, the elevation of sea-level at the centre of the continent due to attraction would amount to about 2900 feet, but that, if the continental mass be assumed to imply a defect of density underneath it, the elevation of the sea at the centre of the continent due to attraction would be only about 10 feet.[1] This subject is further considered in Book III. Part I. Sect. iii.

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[1] *Times*, 7th Decr. 1883. [J. Y. Buchanan.]

The water of the ocean is distinguished from ordinary terrestrial waters by a higher specific gravity, and the presence of so large a proportion of saline ingredients as to impart a strongly salt taste. The average density of sea-water is about 1·026, but it varies slightly in different parts even of the same ocean. According to the observations of J. Y. Buchanan during the *Challenger* expedition, some of the heaviest sea-water occurs in the pathway of the trade-winds of the North Atlantic, where evaporation must be comparatively rapid, a density of 1·02781 being registered. Where, however, large rivers enter the sea, or where there is much melting ice, the density diminishes; Buchanan found among the broken ice of the Antarctic Ocean that it had sunk to 1·02418.[2] A series of soundings taken during the *Vega* expedition in the Kara Sea (lat. 76° 18′, long. 95° 30′ E.) gave a progressive increase of salinity from 1·1 at the surface to 3·4 at 30 fathoms, the surface being freshened by the water poured into the sea by the Siberian rivers.[3]

The greater density of sea-water depends, of course, upon the salts which it contains in solution. At an early period in the earth's history, the water now forming the ocean, together with the rivers, lakes and snowfields of the land, existed as vapour, in which were mingled many other gases and vapours, the whole forming a vast atmosphere surrounding the still intensely hot globe. Under the enormous pressure of the primeval atmosphere, the first condensed water might have had a temperature little below the critical one.[4] In condensing, it would carry down with it many substances in solution. The salts now present in sea-water are to be regarded as principally derived from the primeval constitution of the sea, and thus we may infer that the sea has always been salt. It is probable, however, that, as in the case of the atmosphere, the composition of the ocean-water has acquired its present character only after many ages of slow change, and the abstraction of much mineral matter originally contained in it. There is evidence, indeed, among the geological formations that large quantities of lime, silica, chlorides and sulphates have in the course of time been removed from the sea.[1]

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[1] Bruns, 'Die Figur der Erde,' Berlin, 1876 ; R. S. Woodward, *Bull. U. S. Geol. Surv.* No. 48, p. 85 (1888).

[2] Buchanan, *Proc. Roy. Soc.* (1876), vol. xxiv.

[3] O. Pettersson, 'Vega-Expeditionens Vetenskapliga Iakttagelser,' vol. ii. Stockholm, 1883.

[4] *Q. J. Geol. Soc.* xxxvi. (1880), pp. 112, 117. Fisher, 'Physics of Earth's Crust,' 2nd edit. p. 148.

But it is manifest also that, whatever may have been the original composition of the oceans, they have for a vast section of geological time been constantly receiving mineral matter in solution from the land. Every spring, brook, and river removes various salts from the rocks over which it moves, and these substances, thus dissolved, eventually find their way into the sea. Consequently sea-water ought to contain more or less traceable proportions of every substance which the terrestrial waters can remove from the land—in short, of probably every element present in the outer shell of the globe, for there seems to be no constituent of the earth which may not, under certain circumstances, be held in solution in water. Moreover, unless there be some counteracting process to remove these mineral ingredients, the ocean-water ought to be growing, insensibly perhaps, salter, for the supply of saline matter from the land is incessant. It has been ascertained indeed, with some approach to certainty, that the salinity of the Baltic and Mediterranean is gradually increasing.[2]

The average proportion of saline constituents in the water of the great oceans far from land is about three and a half parts in every hundred of water.[3] But in enclosed seas, receiving much fresh water, it is greatly reduced, while in those where evaporation predominates it is correspondingly augmented. Thus the Baltic water contains from one-seventh to nearly a half of the ordinary proportion in ocean water, while the Mediterranean contains sometimes one-sixth more than that proportion. Forchhammer has shown the presence of the following twenty-seven elements in sea-water: oxygen, hydrogen, chlorine, bromine, iodine, fluorine, sulphur, phosphorus, nitrogen, carbon, silicon, boron, silver, copper, lead, zinc, cobalt, nickel, iron, manganese, aluminium, magnesium, calcium, strontium, barium, sodium, and potassium.[4] To these may be added arsenic, lithium, caesium, rubidium, gold, and probably most if not all of the other elements, though in proportions too minute for detection. The chief constituents have been determined by Dittmar to be present in the proportions shown in the first column of the subjoined tables. Assuming them to occur in the combinations shown in the second column, they are present in the average ratios therein stated[1] :—

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[1] Sterry Hunt supposed that the saline waters of North America derive their mineral ingredients from the sediments and precipitates of the sea in which the Palæozoic rocks were deposited. 'Geological and Chemical Essays,' p. 104.

[2] Paul, in Watts's 'Dictionary of Chemistry,' v. p. 1020. For a detailed study of the Eastern Mediterranean, see the Reports of a Commission, *Denksch. Akad. Wiss.* Vienna, 1892, *et. seq.*

[3] Dittmar's elaborate researches on the samples of ocean water collected by the *Challenger* expedition show that the lowest percentage of salts obtained was 3·301, from the southern part of the Indian Ocean, south of lat. 66°, while the highest was 3·737, from the middle of the North Atlantic, at about lat. 23°. Some valuable results from observations on the waters of the North Atlantic are given by H. Tornöe and L. Schmelck in the *Report of the Norwegian North-Atlantic Expedition*, 1876-1878. The average proportion of salts was found to be from 3·47 to 3·51 per cent, the mean quantities of each constituent as estimated being as follow: $CaCO_3$, 0·002; $CaSo_4$, 0·1395; $MgSO_4$, 0·2071; $MgCl_2$, 0·3561; KCl, 0·0747; $NaHCO_3$, 0·0166; NaCl, 2·682.

[4] Forchhammer, *Phil. Trans.* clv. p. 205. According to Thorpe and Morton (*Chem. Soc. Journ.* xxiv. p. 507), the water of the Irish Sea contains in summer rather more salts than in winter. In 1000 grammes of the summer water of the Irish Sea they found 0·04754

Chlorine	55·292
Bromine	0·188
Sulphuric acid, SO_3	6·410
Carbonic acid, CO_2	0·152
Lime, CaO	1·676
Magnesia, MgO	6·209
Potash, KO	1·332
Soda, Na_2O	41·234
Subtract Basic Oxygen equivalent to the Halogens	12·493
Total Salts	100·000

II.	
Chloride of sodium	77·758
Chloride of magnesium	10·878
Sulphate of magnesia	4·737
Sulphate of lime	3·600
Sulphate of potash	2·465
Bromide of magnesium	0·217
Carbonate of lime	0·345
Total Salts	100·000

Sea-water is appreciably alkaline, its alkalinity being due to the presence of carbonates, of which carbonate of lime is one.[2] In addition to its salts it always contains dissolved atmospheric gases. From the researches conducted during the voyage of the *Bonité* in the Atlantic and Indian Oceans, it was estimated that the gases in 100 volumes of sea-water ranged from 1·85 to 3·04, or from two to three per cent. From observations made during the *Porcupine* cruise of 1868, it was ascertained that the proportion of oxygen was greatest in the surface water, and least in the bottom water. The dissolved oxygen and nitrogen are doubtless absorbed from the atmosphere, the proportion so absorbed being mainly regulated by temperature. According to Dittmar's recent determinations, a litre of sea-water at 0° C. will take up 15·60 cubic centimetres of nitrogen and 8·18 of oxygen, while at 30° C. the proportions sink respectively to 8·36 and 4·17. He regards the carbonic acid as occurring chiefly as carbonates, its presence in the free state being exceptional. During the voyage of the *Challenger*, Buchanan ascertained that the proportion of carbonic acid is always nearly the same for similar temperatures, the amount in the Atlantic surface water, between 20° and 25° C., being 0·0466 gramme per litre, and in the surface Pacific water 0·0268; and that sea-water contains sometimes at least thirty times as much carbonic acid as an equal bulk of fresh

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grammes of carbonate of lime, 0·00503 of ferrous carbonate and traces of silicic acid. For exhaustive chemical investigations regarding the chemistry of ocean water consult Dittmar in vol. i. "Physics and Chemistry," *Report of Voyage of the Challenger*, 1884; also the "Chemistry" part of the *Report of the Norwegian North-Atlantic Expedition*, 1876-1878.

[1] Dittmar, *op. cit.* p. 203 *et seq.* For further reference to the chemistry of sea-water, especially in connection with the action of marine organisms, see *postea*, p. 484.

[2] Dittmar, *op. cit.* p. 206.

water would do.[1] A supposed greater proportion of carbonic acid in the deeper and colder waters of the ocean has been suggested as the main cause of the disappearance of the larger and more delicate calcareous pelagic organisms from abysmal deposits, these forms being more readily attacked and carried away in solution; but according to Dittmar, even alkaline sea-water, if given sufficient time, will take up carbonate of lime in addition to what it already contains.[2] Another of the constituents of sea-water is diffused organic matter, derived from the bodies of dead plants and animals, and no doubt of great importance as furnishing food for the lower grades of animal life.[3]

II.—*The Solid Globe or Lithosphere.*

Within the atmospheric and oceanic envelopes lies the inner solid globe. The only portion of it which, rising above the sea, is visible to us, and forms what we term Land, occupies rather more than one-fourth of the total superficies of the globe, or about 52,000,000 square miles.

§ 1. **The Outer Surface.**—The land is placed chiefly in the northern hemisphere and is disposed in large masses, or continents, which taper southwards to about half the distance between the equator and the south pole. No adequate cause has yet been assigned for the present distribution of the land. It can be shown, however, that portions of the continents are of extreme geological antiquity. There is reason to believe, indeed, that the present terrestrial areas have on the whole been land, or have, at least, never been submerged beneath deep water, from the time of the earliest stratified formations; and that, on the other hand, the ocean-basins have always been vast areas of depression. This subject will be discussed in subsequent pages.

In the New World, the continental trend is approximately north and south; in the Old World, though less distinctly marked, it ranges on the whole east and west. The intimate relation which may be observed between this general trend and the direction of mountain chains, is best exhibited by the American continent. Europe and Africa may be considered as forming, with Asia, the vast continental mass of the Old World. The existing severance of Africa and Europe is of comparatively recent date. On the other hand, Europe and Asia were not always so continuous as at present. But even where the continents of the Old World are separated by sea, the intervening hollows, though now covered by ocean-water, must be regarded as essentially part of the continental areas. Asia is linked with Australia by a chain of islands. The great contrast between the Asiatic and Australian faunas, however, affords good grounds for the belief that, at least for an enormous period of time, Asia and Australia have been divided by an important barrier of sea.

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[1] *Proc. Roy. Soc.* xxiv. According to Mr. Tornoe (*Norwegian North-Atlantic Expedition*, 1876-78, "Chemistry") most of the carbonic acid of sea-water is in combination with soda as bicarbonate of soda. See his memoir for an estimate of the proportion of air in sea-water; also J. Y. Buchanan, *Nature*, xxv. p. 386. Dittmar, *op. cit.* p. 209.

[2] *Op. cit.* p. 222.

[3] Different estimates have been made of the proportion of organic matter. According to the researches of L. Schmelck (*Norwegian North-Atlantic Expedition*, 1876-8, Part ix. p. 4), the proportion is 0·0025 gramme in 100 c.c. of water.

While any good map of the globe enables us to see at a glance the relative positions and areas of the continents and oceans, most maps fail to furnish any data by which the general height or volume of a continent may be estimated. As a rule, the mountain-chains are exaggerated in breadth, and incorrectly indicated, while no attempt is made to distinguish between high plateaux and low plains. In North America, for example, a continuous shaded ridge is placed down the axis of the continent, and marked "Rocky Mountains," while the vast level or gently rolling prairies are left with no mark to distinguish them from the maritime plains of the eastern and southern states. In reality there is no such continuous mountain-chain. The so-called "Rocky Mountains" consist of many independent and sometimes widely separated ridges, having a general meridional trend, and rising above a vast plateau, which is itself 4000 or 5000 feet in elevation. It is not these intermittent ridges which really form the great mass of the land in that region, but the widely extended lofty plateau, or rather succession of plateaux, which supports them. In Europe, also, the Alps form but a subordinate part of the total bulk of the land. If their materials could be spread out over the continent, it has been calculated that they would not increase its height more than about twenty-one feet.[1]

Attempts have been made to estimate the probable average height which would be attained if the various inequalities of the land could be levelled down. Humboldt estimated the mean height of Europe to be about 671, of Asia 1132, of North America 748, and of South America 1151 feet.[2] Herschel supposed the mean height of Africa to be 1800 feet.[3] These figures, though based on the best data available at the time, are no doubt much under the truth. In particular, the average height assigned to North America is evidently far less than it should be; for the great plains west of the Mississippi valley reach an altitude of about 5000 feet, and serve as the platform from which the mountain ranges rise. The height of Asia also is obviously much greater than this old estimate. G. Leipoldt has computed the mean height of Europe to be 296·838

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[1] M. De Lapparent ('Traité de Géologie,' 3rd edit. p. 57) gives the following estimate of relative heights and areas, the area below sea-level being taken as 0·6 of the whole.

Zone I.	(from sea-level	to 200 metres)	covers	34·7	per cent of the	terrestrial surface.
,, II.	,,	200 ,, 500	,,	21·6	,,	,,
,, III.	,,	500 ,, 1000	,,	21·4	,,	,,
,, IV.	,,	1000 ,, 2000	,,	14·2	,,	,,
,, V.	,,	2000 ,, 3000	,,	3·7	,,	,,
,, VI.	,,	3000 ,, 4000	,,	2·1	,,	,,
,,VII.	,,	above ,, 4000	,,	1·7	,,	,,
				——	,,	,,
				99·4	,,	,,

[2] 'Asie Centrale,' tom. i. p. 168.

[3] 'Physical Geography,' p. 119.

metres (973·628 feet).[1] Prof. A. De Lapparent makes the mean height of the land of the globe 2120 feet, and estimates the mean height of Europe to be 958 feet, Asia 2884, Africa 1975, North America 1952, and South America 1762.[2] Dr. John Murray computes these heights as follows: Europe 939, Asia 3189, Africa 2021, North America 1888, South America 2078, Australia 805 feet, general mean height of land 2252 feet.[3] It is of some consequence to obtain as near an approximation to the truth in this matter as may be possible, in order to furnish a means of comparison between the relative bulk of different continents, and the amount of material on which geological changes can be effected.

The highest elevation of the surface of the land is the summit of Mount Everest, in the Himalaya range (29,000 feet); the deepest depression not covered by water is that of the shores of the Dead Sea (1300 feet below sea-level). There are, however, many subaqueous portions of the land which sink to greater depths. The bottom of the Caspian Sea, for instance, lies about 3000 feet below the general sea-level. The vertical difference between the highest point of the land and the maximum known depth of the sea is 56,932 feet or nearly 11 miles.

There are two conspicuous junction-lines of the land with its overlying and surrounding envelopes. First, with the Air, expressed by the contours or relief of the land. Second, with the Sea, expressed by coast-lines.

(1.) Contours or Relief of the Land.—While the surface of the land presents endless diversities of detail, its leading features may be generalised as mountains, table-lands, and plains.

Mountains.—The word "mountain" is, properly speaking, not a scientific term. It includes many forms of ground utterly different from each other in size, shape, structure, and origin. It is popularly applied to any considerable eminence or range of heights, but the height and size of the elevated ground so designated vary indefinitely. In a really mountainous country the word would be restricted to the loftier masses of ground, while such a word as hill would be given to the lesser heights. But in a region of low or gently undulating land, where any conspicuous eminence becomes important, the term mountain is lavishly used. In Eastern America this habit has been indulged in to such an extent, that what are, so to speak, mere hummocks in the general landscape, are dignified by the name of mountains.

It is hardly possible to give a precise scientific definition to a term so vaguely employed in ordinary language. When a geologist uses the word, he must either be content to take it in its familiar vague sense, or must add some phrase defining the meaning which he attaches to it. He finds that there are three leading and totally distinct types of elevation which are all popularly termed mountains. 1. Single eminences; standing alone upon a plain or table-land. This is essentially the volcanic type. The huge cones of Vesuvius, Etna, and Teneriffe, as well as the smaller ones so abundant in volcanic districts, are examples of it. There occur, however, occasional isolated eminences that stand up as remnants of once extensive rock-formations. These have no real analogy with volcanic elevations, but should be classed under the next type. The remarkable *buttes* of Western America are good illustrations of them. 2. Groups of eminences connected at the sides or base, often forming lines of ridge between divergent valleys, and owing their essential forms not to underground structure so much as to superficial erosion. Many of the more ancient uplands, both in the Old World and the New, furnish examples of this type, such as the Highlands of Scotland, the hills of Cumberland and Wales, the high grounds between Bohemia and Bavaria, the Laurentide Mountains of Canada, and the Green and White Mountains of New England. 3. Lines of lofty ridge rising into a succession of more or less distinct summits, their general external form having relation to an internal plication of their component rocks. These linear elevations, whose existence and trend have been determined immediately by subterranean movement, are the true mountain-ranges of the globe. They may be looked upon as the crests of the great waves into which the crust of the earth has been thrown. All the great mountain-lines of the world belong to this type.

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[1] 'Die Mittlere Hohe Europas,' Leipzig, 1874. In this work the mean height of Switzerland is put down as 1299·91 metres; Spanish peninsula, 700·60; Austria, 517·87; Italy, 517·17; Scandinavia, 428·10; France, 393·84; Great Britain, 217·70; German Empire, 213·66; Russia, 167·09; Belgium, 163·36; Denmark (exclusive of Iceland), 35·20; the Netherlands (exclusive of Luxembourg and the tracts below sea-level), 9·61.

[2] 'Traité,' p. 56.

[3] *Scottish Geog. Mag.* iv. (1888), 23.

Leaving the details of mountain-form to be described in Book VII., we may confine our attention here to a few of the more important general features. In elevations of the third or true mountain type, there may be either one line or range of heights, or a series of parallel and often coalescent ranges. In the Western Territories of the United States, the vast plateau has been, as it were, wrinkled by the uprise of long intermittent ridges, with broad plains and basins between them. Each of these forms an independent mountain-range. In the heart of Europe, the Bernese Oberland, the Pennine, Lepontine, Rhaetic, and other ranges form one great Alpine chain or system.

In a great mountain-chain, such as the Alps, Himalayas, or Andes, there is one general persistent trend for the successive ridges. Here and there, lateral offshoots may diverge, but the dominant direction of the axis of the main chain is generally observed by its component ridges until they disappear. Yet while the general parallelism is preserved, no single range may be traceable for more than a comparatively short distance ; it may be found to pass insensibly into another, while a third may be seen to begin on a slightly different line, and to continue with the same dominant trend until it in turn becomes confluent. The various ranges are thus apt to assume an arrangement *en échelon.*

The ranges are separated by *longitudinal* valleys, that is, depressions coincident with the general direction of the chain. These, though sometimes of great length, are relatively of narrow width. The valley of the Rhône, from the source of the river down to Martigny, offers an excellent example. By a second series of valleys the ranges are trenched, often to a great depth, and in a direction transverse to the general trend. The Rhône furnishes also an example of one of these *transverse* valleys, in its course from Martigny to the Lake of Geneva. In most mountain regions, the heads of two adjacent transverse valleys are often connected by a depression or *pass* (*col*, *joch*).

A large block of mountain ground, rising into one or more dominant summits, and more or less distinctly defined by longitudinal and traverse valleys, is termed in French a *massif*—a word for which there is no good English equivalent. Thus in the Swiss Alps we have the massifs of the Glärnisch, the Tödi, the Matterhorn, the Jungfrau, &c.

Very exaggerated notions are common regarding the angle of declivity in mountains. Sections drawn across any mountain or mountain-chain on a true scale, that is, with the length and height on the same scale, bring out the fact that, even in the loftiest mountains, the breadth of base is always very much greater than the height. Actual vertical precipices are less frequent than is usually supposed, and even when they do occur, generally form minor incidents in the declivities of mountains. Slopes of more than 30° in angle are likewise far less abundant than casual tourists believe. Even such steep declivities as those of 38° or 40° are most frequently found as *talus*-slopes at the foot of crumbling cliffs, and represent the angle of repose of the disintegrated débris. Here and there, where the blocks loosened by weathering are of large size, they may accumulate upon each other in such a manner that for short distances the average angle of declivity may mount as high as 65°. But such steep slopes are of limited extent. Declivities exceeding 40°, and bearing a large proportion to the total dimensions of hill or mountain, are always found to consist of naked solid rock. In estimating angles of inclination from a distance, the student will learn by practice how apt is the eye to be deceived by perspective and to exaggerate the true declivity, sometimes to mistake a horizontal for a highly inclined or vertical line. The mountain outline shown in Fig. 2 presents a slope of 25° between *a* and *b*, of 45° between *b* and *c*, of 17° between *c* and *d*, of 40° between *d* and *e*, and of 70° between *e* and *f*. At a great distance, or with bad conditions of atmosphere, these might be believed to be the real declivities. Yet if the same angles be observed in another way (as on a cottage roof at B), we may learn that an apparently inclined surface may really be horizontal (as from *a* to *b* and from *c* to *d*), and that by the effect of perspective, slopes may be made to appear much steeper than they really are.[1]

Much evil has resulted in geological research from the use of exaggerated angles of slope in sections and diagrams. It is therefore desirable that the student should, from the beginning, accustom himself to the drawing of outlines as nearly as possible on a true scale. The accompanying section of the Alps by De la Beche (Fig. 3) is of interest in this respect, as one of the earliest illustrations of the advantage of constructing geological sections on a true scale as to the relative proportions of height and length.[1]

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[1] Mr. Ruskin has well illustrated this point. See 'Modern Painters,' vol. iv. p. 183, whence the illustrations in the text are taken.

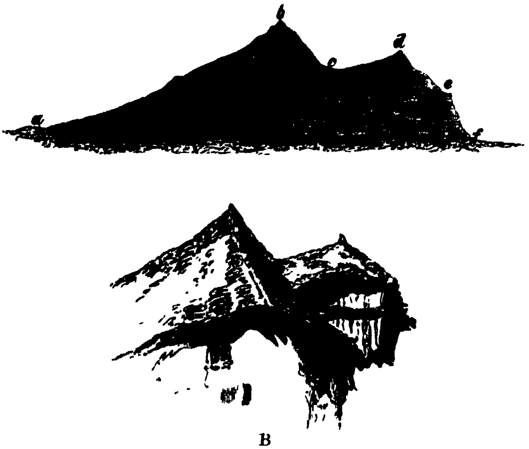

Fig. 2.—Angles of Slope where the eye may be deceived by perspective. (After Ruskin.) A, Mountain outline ; B, The same outline as shown by cottage roof.

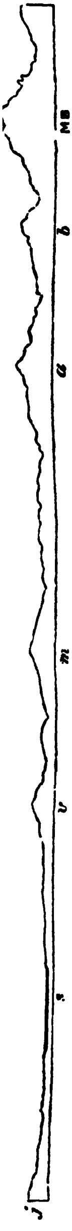

Fig. 3.—Section from the Jura to Mont Blanc, on the same scale for length and height. j, Jura; s, Lake of Geneva; v, Voirons; m, Mole; a, Aiguille de Varens; b, Brevent; MB, Mont Blanc.

Table-lands or *Plateaux* are elevated regions of flat or undulating country, rising to heights of 1000 feet and upwards above the level of the sea. They are sometimes bordered with steep slopes, which descend from their edges, as the table-land of the Spanish peninsula does into the sea. In other cases, they gradually sink into the plains and have no definite boundaries; thus the prairie-land west of the Missouri slowly and imperceptibly ascends until it becomes a vast plateau from 4000 to 5000 feet above the sea. Occasionally a high table-land is encircled with lofty mountains, as in those of Quito and Titicaca among the Andes, and that of the heart of Asia; or it forms in itself the platform on which lines of mountains stand, as in North America, where the ranges included within the Rocky Mountains reach elevations of from 10,000 to 14,000 feet above the sea, but not more than from 5000 to 10,000 feet above the table-land.

Two types of table-land structure may be observed. 1. Table-lands consisting of level or gently undulated sheets of rock, the general surface of the country corresponding with that of the stratification. The Rocky Mountain plateau is an example of this type, which may be called that of Deposit, for the flat strata have been equably upraised nearly in the position in which they were deposited. 2. Table-lands formed out of contorted, crystalline, or other rocks, which have been planed down by superficial agents. This type, where the external form is independent of geological structure, may be termed that of Erosion. The *fjelds* of Norway are portions of such a table-land. In proportion to its antiquity, a plateau is trenched by running water into systems of valleys, until in the end it may lose its plateau character and pass into the second type of mountain-ground above described. This change has largely altered the ancient table-land of Scandinavia, as will be illustrated in Book VII.

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[1] 'Sections and Views, illustrative of Geological Phenomena,' 1830. *Geol. Observer*, p. 646.

Plains are tracts of lowland (under 1000 feet in height) which skirt the sea-board of the continents and stretch inland up the river valleys. The largest plain in the world is that which, beginning in the centre of the British Islands, stretches across Europe and Asia. On the west, it is bounded by the ancient table-lands of Scandinavia, Scotland and Wales on the one hand, and those of Spain, France and Germany on the other. Most of its southern boundary is formed by the vast belt of high ground which spreads from Asia Minor to the east of Siberia. Its northern margin sinks beneath the waters of the Arctic Ocean. This vast region is divided into an eastern and western tract by the low chain of the Ural Mountains, south of which its general level sinks, until underneath the Caspian Sea it reaches a depression of about 3000 feet below sea-level. Along the eastern sea-board of America lies a broad belt of low plains, which attain their greatest dimensions in the regions watered by the larger rivers. Thus they cover thousands of square miles on the north side of the Gulf of Mexico, and extend for hundreds of miles up the valley of the Mississippi. Almost the whole of the valleys of the Orinoco, Amazon and La Plata is occupied with vast plains.

From the evidence of upraised marine shells, it is certain that large portions of the great plain of the Old World comparatively recently formed part of the sea-floor. It is likewise probable that the beds of some enclosed sea-basins, such as that of the North Sea, have formerly been plains of the dry land.

It is obvious, from their distribution along river-valleys, and on the areas between the base of high grounds and the sea, that plains are essentially areas of deposit. They are the tracts that have received the detritus washed down from the slopes above them, whether that detritus has originally accumulated on the land or below the sea. Their surface presents everywhere loose sandy, gravelly, or clayey formations, indicative of its comparatively recent subjection to the operation of running water.

(2.) Coast-lines.—A mere inspection of a map of the globe brings before the mind the striking differences which the masses of land present in their line of junction with the sea. As a rule, the southern continents possess a more uniform unindented coast-line than the northern. It has been estimated that the ratios between area and coast-line among the different continents, stand approximately as in the following table :—

Northern.	Europe has 1 geographical mile of	coast-line to	143	square miles of surface.
	North America	,,	,,	265	,,
	Asia, including the islands		,,	469	,,
Southern.	Africa	,,	,,	895	,,
	South America	,,	,,	434	,,
	Australia	,,	,,	332	,,

In estimating the relative potency of the sea and of the atmospheric agents of disintegration, in the task of wearing down the land, it is evidently of great importance to take into account the amount of surface respectively exposed to their operations. Other things being equal, there is relatively more marine erosion in Europe than in North America. But we require also to consider the nature of the coast-line, whether flat and alluvial, or steep and rocky, or with some intermediate blending of these two characters. By attending to this point, we are soon led to observe such great differences in the character of coast-lines, and such an obvious relation to differences of geological structure, on the one hand, and to diversities in the removal or deposit of material, on the other, as to suggest that the present coast-lines of the globe cannot be aboriginal, but must be referred to the operation of geological agents still at work. This inference is amply sustained by more detailed investigation. While the general distribution of land and water must undoubtedly be assigned to terrestrial movements affecting the solid globe, the present actual coasts of the land have chiefly been produced by local causes. Headlands project from the land because, for the most part, they consist of rock which has been better able to withstand the shock of the breakers. Bays and creeks, on the other hand, have been cut by the waves out of less durable materials. Again, by the sinking of land, ranges of hills have become capes and headlands, while the valleys have passed into the condition of bays, inlets, or fjords. By the uprise of the sea-bottom, tracts of low alluvial ground have been added to the land. Hence, speculations as to the history of the elevation of the land, based merely upon inferences from the form of coast-lines as expressed upon ordinary maps, to be of real service, demand a careful scrutiny of the actual coast-lines, and an amount of geological investigation which would require long and patient toil for its accomplishment.

Passing from the mere external form of the land to the composition and structure of its materials, we may begin by considering the general density of the entire globe, computed from observations and compared with that of the outer and accessible portion of the planet. Reference has already been made to the comparative density of the earth among the other members of the solar system. In inquiries regarding the history of our globe, the density of the whole mass of the planet, as compared with water—the standard to which the specific gravities of terrestrial bodies are referred—is a question of prime importance. Various methods have been employed for determining the earth's density. The deflection of the plumb-line on either side of a mountain of known structure and density, the time of oscillation of the pendulum at great heights, at the sea-level, and in deep mines, and the comparative force of gravitation as measured by the torsion balance, have each been tried with the following various results :—

Plumb-line experiments on Schichallien (Maskelyne and Playfair) gave as the mean density of the earth	4·713
Do. on Arthur's Seat, Edinburgh (James)	5·316
Pendulum experiments on Mont Cenis (Carlini and Giulio)	4·950
Do. in Harton coal-pit, Newcastle (Airy)	6·565
Torsion balance experiments (Cavendish, 1798)	5·480
Do. do. (Reich, 1838)	5·49
Do. do. (Baily, 1843)	5·660
Do. do. (Cornu and Baille, 1872–3)	5·50–5·56

Though these observations are somewhat discrepant, we may feel satisfied that the globe has a mean density neither much more nor much less than 5·5 ; that is to say, it is five and a half times heavier than one of the same dimensions formed of pure water. Now the average density of the materials which compose the accessible portions of the earth is between 2·5 and 3 ; so that the mean density of the whole globe is about twice as much as that of its outer part. We might, therefore, infer that the inside consists of much heavier materials than the outside, and consequently that the mass of the planet must contain at least two dissimilar portions—an exterior lighter crust or rind, and an interior heavier nucleus. But the effect of pressure must necessarily increase the specific gravity of the interior, as will be alluded to further on.

§ 2. **The Crust.**—It was formerly a prevalent belief that the exterior and interior of the globe differed from each other to such an extent that, while the outer parts were cool and solid, the vastly more enormous inner intensely hot part was more or less completely liquid. Hence the term "crust" was applied to the external rind in the usual sense of that word. This crust was variously computed to be ten, fifteen, twenty, or more miles in thickness. In the accompanying diagram (Fig. 4), for example, the thick line forming the circle represents a relative thickness of 100 miles. There are so many proofs of enormous and wide-spread corrugation of the materials of the earth's outer layers, and such abundant traces of former volcanic action, that geologists have naturally regarded the doctrine of a thin crust over a liquid interior as necessary for the explanation of a large class of terrestrial phenomena. For reasons which will be afterwards given, however, this doctrine has been

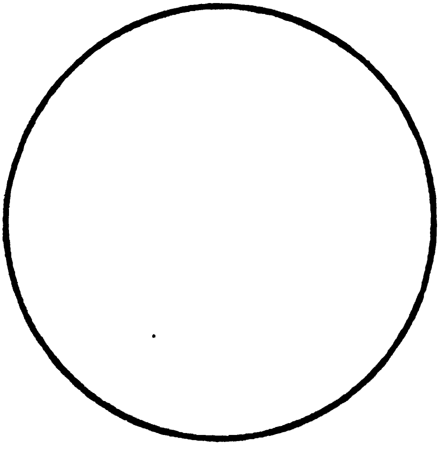

Fig. 4.—Supposed Crust of the Earth, 100 Miles thick.

opposed by eminent physicists, and is now abandoned by most geologists. Nevertheless the term "crust" continues to be used, apart from all theory regarding the nucleus, as a convenient word to denote those cool, upper or outer layers of the earth's mass in the structure and history of which, as the only portions of the planet accessible to human observation, lie the chief materials of geological investigation. The chemical and mineral constitution of the crust is fully discussed in later pages (p. 60 *et seq.*)

§ 3. **The Interior or Nucleus.**—Though the mere outside skin of our planet is all with which direct acquaintance can be expected, the irregular distribution of materials beneath the crust may be inferred from the present distribution of land and water, and the observed differences in the amount of deflection of the plumb-line near the sea and near mountain chains. The fact that the southern hemisphere is almost wholly covered with water, appears only explicable, as already remarked, on the assumption of an excess of density in the mass of that half of the planet. The existence of such a vast sheet of water as that of the Pacific Ocean is to be accounted for, says Archdeacon Pratt, by the presence of "some excess of matter in the solid parts of the earth between the Pacific Ocean and the earth's centre, which retains the water in its place, otherwise the ocean would flow away to the other parts of the earth."[1] The same writer points out that a deflection of the plumb-line towards the sea, which has in a number of cases been observed, indicates that "the density of the crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed."[2] Apart, therefore, from the depressions of the earth's surface, in which the oceans lie, we must regard the internal density, whether of crust or nucleus, to be somewhat irregularly arranged,—there being an excess of heavy materials in the water-hemisphere, and beneath the ocean-beds as compared with the continental masses.

It has been argued from the difference between the specific gravity of the whole globe and that of the crust, that the interior must consist of heavier material, and may be metallic. But the effect of the enormous internal pressure, it might be supposed, should make the density of the nucleus much higher, even if the interior consisted of matter which, on the surface, would be no heavier than that of the crust. In fact, we might, on the contrary, argue for the probable comparative lightness of the substance composing the nucleus. That the total density of the planet does not greatly exceed its observed amount, may indicate that some antagonistic force counteracts the effect of pressure. The only force we can suppose capable of so acting is heat, though to what extent this counterbalancing takes place is still unknown. It must be admitted that we are still in ignorance of the law that regulates the compression of solids under such vast pressure as must exist within the earth's interior. We know that gases and vapours may be compressed into liquids, sometimes even into solids, and that in the liquid condition another law of compressibility begins. We know also from experiment that some substances have their melting-point raised by pressure.[1] It may be that the same effect takes place within the earth; that pressure increasing inward to the centre of the globe, while augmenting the density of each successive shell, may retain the whole in a solid condition, yet at temperatures far above the normal melting-points at the surface. Hence, on this view of the matter, it is conceivable that the difference between the density of the whole globe and that of the crust may be due to pressure, rather than to any essential difference of composition. Laplace proposed the hypothesis that the increase of the square of the density is proportional to the increase of the pressure, which gives a density of 8·23 at half the terrestrial radius and of 10·74 at the centre. From another law proposed by Prof. Darwin, the density at half the radius is only 7·4 but thence towards the centre increases rapidly up to infinity.[2] Dr. Pfaff believes that the mean terrestrial density of 5·5 is not incompatible with the notion that the whole globe consists of materials of the same density as the rocks of the crust.[3] It is possible that the gases dissolved in the hot magma of the nucleus, with their very high tension, may counteract the effects of compression and thus reduce density.

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[1] 'Figure of the Earth,' 4th edit. p. 236.

[2] *Op. cit.* p. 200. See also Herschel, 'Phys. Geog.' § 13; O. Fisher, *Cambridge Phil. Trans.* xii. part ii.; 'Physics of the Earth's Crust,' p. 75. *Phil. Mag.* July, 1886. Faye, *Comptes rendus*, cii. (1886), p. 651.

Analogies in the solar system, however, as well as the actual structure of the rocky crust of the globe, suggest that heavier metallic ingredients possibly predominate in the nucleus. If the materials of the globe were once, as they are believed to have been, in a liquid condition, they would then doubtless be subject to internal arrangement, in accordance with their relative specific gravities. We may conceive that, as in the case of the sun, as well as of the solar system generally (*ante*, p. 9), there would be, so long as internal mobility lasted, a tendency in the denser elements of our planet to gravitate towards the centre, in the lighter to accumulate outside. That a distribution of this nature has certainly taken place to some extent, is evident from the structure of the envelopes and crust. It is what might be expected, if the constitution of the globe resembles, on a small scale, the larger planetary system of which it forms a part. The existence even of a metallic interior has been inferred from the metalliferous veins which traverse the crust, and which are commonly supposed to have been filled from below.

Evidence of Internal Heat.—In the evidence obtainable as to the former history of the earth, no fact is of more importance than the existence of a high temperature beneath the crust, which has now been placed beyond all doubt. This feature of the planet's organisation is made clear by the following proofs:—

(1.) *Volcanoes*.—In many regions of the earth's surface, openings exist from which steam and hot vapours, ashes and streams of molten rock, are from time to time emitted. The abundance and wide diffusion of these openings, inexplicable by any mere local causes, must be regarded as indicative of a very high internal temperature. If to the still active vents of eruption, we add those which have formerly been the channels of communication between the interior and the surface, there are perhaps few large regions of the globe where proofs of volcanic action cannot be found. Everywhere we meet with masses of molten rock which have risen from below, as if from some general reservoir. The phenomena of active volcanoes are fully discussed in Book III. Part I.

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[1] Under a pressure of 792 atmospheres, spermaceti has its melting-point raised from 51° to 80·2°, and wax from 64·5° to 80·2°.

[2] See Fisher 'Physics of Earth's Crust,' 2nd edit. chap. ii. Legendre supposed that the density being 2·5 at the surface, it is 8·5 at half the length of the radius and 11·3 at the centre. More recently E. Roche calculated these densities to be 2·1, 8·5, and 10·6 respectively.

[3] 'Allgemeine Geologie als exacte Wissenschaft,' p. 42.

(2.) *Hot Springs.*—Where volcanic eruptions have ceased, evidence of a high internal temperature is still often to be found in springs of hot water which continue for centuries to maintain their heat. Thermal springs, however, are not confined to volcanic districts. They sometimes rise even in regions many hundreds of miles distant from any active volcanic vent. The hot springs of Bath (temp. 120° Fahr.) and Buxton (temp. 82° Fahr.) in England are fully 900 miles from the Icelandic volcanoes on the one side, and 1100 miles from those of Italy and Sicily on the other.

(3.) *Borings, Wells and Mines.*—The influence of the seasonal changes of temperature extends downward from the surface to a depth which varies with latitude, with the thermal conductivity of soils and rocks, and perhaps with other causes. The cold of winter and the heat of summer may be regarded as following each other in successive waves downward, until they disappear along a limit at which the temperature remains constant. This zone of invariable temperature is commonly believed to lie at a depth of somewhere between 60 and 80 feet in temperate regions. At Yakutsk in Eastern Siberia (lat. 62° N.), however, as shown in a well-sinking, the soil is permanently frozen to a depth of about 700 feet.[1] In Java, on the other hand, a constant temperature is said to be met with at a depth of only 2 or 3 feet.[2]

It is a remarkable fact, now verified by observation all over the world, that below the limit of the influence of ordinary seasonal changes the temperature, so far as we yet know, is nowhere found to diminish downwards. It always rises; and its rate of increment never falls much below the average. The only exceptional cases occur under circumstances not difficult of explanation. On the one hand, the neighbourhood of hot-springs, of large masses of lava, or of other manifestations of volcanic activity, may raise the subterranean temperature much above its normal condition; and this augmentation may not disappear for many thousand years after the volcanic activity has wholly ceased, since the cooling down of a subterranean mass of lava must necessarily be a very slow process. Lord Kelvin has even proposed to estimate the age of subterranean masses of intrusive lava from their excess of temperature above the normal amount for their isogeotherms (lines of equal earth-temperature), some probable initial temperature and rate of cooling being assumed. On the other hand, the spread of a thick mass of snow and ice over any considerable area of the earth's surface, and its continuance there for several thousand years, would so depress the isogeotherms that, for many centuries afterwards, there would be a fall of temperature for a certain distance downwards. At the present day, in at least the more northerly parts of the northern hemisphere, there are such evidences of a former more rigorous climate, as in the well-sinking at Yakutsk just referred to.[1] Lord Kelvin (Sir W. Thomson)[2] has calculated that any considerable area of the earth's surface covered for several thousand years by snow or ice, and retaining, after the disappearance of that frozen covering, an average surface temperature of 13° C., "would during 900 years show a decreasing temperature for some depth down from the surface, and 3600 years after the clearing away of the ice would still show residual effect of the ancient cold, in a half rate of augmentation of temperature downwards in the upper strata, gradually increasing to the whole normal rate, which would be sensibly reached at a depth of 600 metres."

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[1] Helmersen, *Brit. Assoc. Rep.* 1871, p. 22. See vol. for 1886, p. 271.

[2] Junghuhn's 'Java,' ii. p. 771.

Beneath the limit to which the influence of the changes of the seasons extends, observations all over the globe, and at many different elevations, give a rate of increase of temperature downwards, or "temperature gradient," which has been usually taken to be 1° Fahr. for every 50 or 60 feet of descent, this computation being based especially on observations in deep mines and borings. Professor Prestwich concluded from a large series of observations collated by him, that the average increment might be taken at 1° Fahr. for every 45 feet.[3] Observations taken in the extraordinarily deep boring at Schladebach, near Dürrenberg, showed that in a depth of 5736 feet the average rise of temperature was 1° Fahr. for every 65 feet.[4] According to data collected by a Committee of the British Association, the average gradient appears to be 1° Fahr. for every 64 feet, or $\frac{1}{64}$ of a degree per foot.

Isogeotherms near the surface follow approximately the contours of the surface, but are flatter than these, and "their flattening increases as we pass to lower ones, until at a considerable depth they become sensibly horizontal planes. The temperature gradient is consequently steepest beneath gorges and least steep beneath ridges."[5]

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[1] Professor Prestwich (*Inaugural Lecture*, 1875, p. 45) has suggested that to the more rapid refrigeration of the earth's surface during this cold period, and to the consequent depression of the subterranean isothermal lines, the alleged present comparative quietude of the volcanic forces is to be attributed, the internal heat not having yet recovered its dominion in the outer crust.

[2] *Brit. Assoc. Reports*, 1876, Sections, p. 3.

[3] *Proc. Roy. Soc.* xli. (1885), p. 55.

[4] *Brit. Assoc.* 1889. Report of Underground Temperature Committee.

[5] J. D. Everett, *Brit. Assoc.* 1879, Sections, p. 345. Compare also the elaborate observations made in the St. Gothard Tunnel, F. Stapff, 'Rapports, Conseil Féd. St. Gothard,' vol. viii., and 'Geologische Durchschnitte des Gothard Tunnels;' 'Étude de l'Influence de la Chaleur de l'Intérieur de la Terre,' &c., *Revue Univ. Mines*, 1879-80. *Min. Proc. N. England Inst. Mining-Mechan. Engin.* xxxii. (1883), p. 19. 'Reports of Committee on Underground Temperature,' *Brit. Assoc. Rep.* from 1868 onwards, with summary of results in the volume for 1882. A voluminous and valuable collection of data bearing on this subject was compiled by Professor Prestwich and is published in *Proc. Roy. Soc.* xli. (1885), p. 1.

Irregularities in the Downward Increment of Heat.—While there is everywhere a progressive increase of temperature downwards, its rate is by no means uniform. The more detailed observations which have been made in recent years have brought to light the important fact that considerable variations in the rate of increase take place, even in the same bore. The temperatures obtained at different depths in the Rose Bridge colliery shaft, Wigan, for instance, read as in the following columns:—

Depth in Yards.	Temperature (Fahr.)	Depth in Yards.	Temperature (Fahr.)
558	78	745	89
605	80	761	90½
630	83	775	91½
663	85	783	92
671	86	800	93
679	87	806	93½
734	88½	815	94

At La Chapelle, in an important well made for the water-supply of Paris, observations have been taken of the temperature at different depths, as shown in the subjoined table:[1]—

Depth in Metres.	Temperature (Fahr.)	Depth in Metres.	Temperature (Fahr.)
100	59·5	500	72·6
200	61·8	600	75·0
300	65·5	660	76·0
400	69·0		

In drawing attention to the foregoing temperature-observations at the Rose Bridge colliery—the deepest mine in Great Britain—Professor Everett points out that, assuming the surface temperature to be 49° Fahr., in the first 558 yards, the rate of rise of temperature is 1° for 57·7 feet; in the next 257 yards it is 1° in 48·2 feet; in the portion between 605 and 671 yards—a distance of only 198 feet—it is 1° in 33 feet; in the lowest portion of 432 feet it is 1° in 54 feet.[2] When such irregularities occur in the same vertical shaft, it is not surprising that the average should vary so much in different places.

There can be little doubt that one main cause of these variations is to be sought in the different thermal conductivities of the rocks of the earth's crust. The first accurate measurements of the conducting powers of rocks were made by the late J. D. Forbes at Edinburgh (1837-1845). He selected three sites for his thermometers, one in "trap-rock" (a porphyrite of Lower Carboniferous age), one in loose sand, and one in sandstone, each set of instruments being sunk to depths of 3, 6, 12 and 24 French feet from the surface. He found that the wave of summer heat reached the bulb of the deepest instrument (24 feet) on 4th January in the trap-rock, on 25th December in the sand,

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[1] *Brit. Assoc. Rep.* 1873, Sections, p. 254. [2] *Brit. Assoc. Rep.* 1870, Sections, p. 31.

and on 3rd November in the sandstone, the trap-rock being the worst conductor and the solid sandstone by far the best.[1]

As a rule, the lighter and more porous rocks offer the greatest resistance to the passage of heat, while the more dense and crystalline offer the least resistance. The resistance of opaque white quartz is expressed by the number 114, that of basalt stands at 273, while that of cannel coal stands very much higher at 1538, or more than thirteen times that of quartz.[2]

It is evident also, from the texture and structure of most rocks, that the conductivity must vary in different directions through the same mass, heat being more easily conducted along than across the "grain," the bedding, and the other numerous divisional surfaces. Experiments have been made to determine these variations in a number of rocks. Thus, the conductivity in a direction transverse to the divisional planes being taken as unity, the conductivity parallel with these planes was found in a variety of magnesian schist to be 4·028. In certain slates and schistose rocks from central France, the ratio varied from 1 : 2·56 to 1 : 3·952. Hence in such fissile rocks as slate and mica-schist, heat may travel four times more easily along the planes of cleavage or foliation than across them.[3]

In reasoning upon the discrepancies in the rate of increase of subterranean temperatures, we must also bear in mind that convection by percolating streams of water must materially affect the transference of heat from below.[4] Certain kinds of rock are more liable than others to be charged with water, and, in almost every boring or shaft, one or more horizons of such water-bearing rocks are met with. The effect of interstitial water is to diminish thermal resistance. Dry red brick has its resistance lowered from 680 to 405 by being thoroughly soaked in water, its conductivity being thus increased 68 per cent. A piece of sandstone has its conductivity heightened to the extent of 8 per cent by being wetted.[5]

Mallet contended that the variations in the amount of increase in subterranean temperature are too great to permit us to believe them to be due merely to differences in the transmission of the general internal heat, and that they point to local accessions of heat arising from transformation of the mechanical work of compression, which is due to the constant cooling and contraction of the globe.[6] But it may be replied that these variations are not greater than, from the known divergences in the conductivities of rocks, they might fairly be expected to be.

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[1] *Trans. Roy. Soc. Edin.* xvi. p. 211.

[2] Herschel and Lebour (British Association Committee on Thermal Conductivities of Rocks), *Brit. Assoc. Rep.* 1875, p. 59. The final Report is in the vol. for 1881.

[3] "Report of Committee on Thermal Conductivities of Rock," *Brit. Assoc. Rep.* 1875, p. 61. Jannettaz, *Bull. Soc. Géol. France* (April-June, 1874), ii. p. 264. This observer has carried out a series of detailed researches on the propagation of heat through rocks which will be found in *Bull. Soc. Géol. France*, tomes i.-ix. (3rd series).

[4] In the great bore of Sperenberg (4172 feet, entirely in rock-salt, except the first 283 feet) there is evidence that the water near the top is warmed 4½° Fahr. by convection. *Brit. Assoc.* 1882, p. 78.

[5] Herschel and Lebour, *Brit. Assoc. Rep.* 1875, p. 58.

[6] "Volcanic Energy," *Phil. Trans.* 1875.

Probable Condition of the Earth's Interior.—Various theories have been propounded on this subject. There are only three which merit serious consideration. (1.) One of these supposes the planet to consist of a solid crust and a molten interior. (2.) The second holds that, with the exception of local vesicular spaces, the globe is solid and rigid to the centre. (3.) The third contends that while the mass of the globe is solid, there lies a liquid substratum beneath the crust.

1. *The arguments in favour of internal liquidity* may be summed up as follows. (*a.*) The ascertained rise of temperature inwards from the surface is such that, at a very moderate depth, the ordinary melting-point of even the most refractory substances would be reached. At 20 miles the temperature, if it increases progressively, as it does in the depths accessible to observation, must be about 1760° Fahr.; at 50 miles it must be 4600°, or far higher than the fusing-point even of so stubborn a metal as platinum, which melts at 3080° Fahr.[1] (*b.*) All over the world volcanoes exist from which steam and torrents of molten lava are from time to time erupted. Abundant as are the active volcanic vents, they form but a small proportion of the whole which have been in operation since early geological time. It has been inferred, therefore, that these numerous funnels of communication with the heated interior could not have existed and poured forth such a vast amount of molten rock, unless they drew their supplies from an immense internal molten nucleus. (*c.*) When the products of volcanic action from different and widely-separated regions are compared and analysed, they are found to exhibit a remarkable uniformity of character. Lavas from Vesuvius, from Hecla, from the Andes, from Japan, and from New Zealand present such an agreement in essential particulars as, it is contended, can only be accounted for on the supposition that they have all emanated from one vast common source.[2] (*d.*) The abundant earthquake-shocks which affect large areas of the globe are maintained to be inexplicable unless on the supposition of the existence of a thin and somewhat flexible crust. These arguments, it will be observed, are only of the nature of inferences drawn from observations of the present constitution of the globe. They are based on geological data, and have been frequently urged by geologists as supporting the only view of the nature of the earth's interior, supposed by them to be compatible with geological evidence.

2. *The arguments in favour of the internal solidity of the earth* are based on physical and astronomical considerations of the greatest importance. They may be arranged as follows:—

(*a.*) Argument from precession and nutation.—The problem of the internal condition of the globe was attacked as far back as the year 1839 by Hopkins, who calculated how far the planetary motions of precession and nutation would be influenced by the solidity or liquidity of the earth's interior. He found that the precessional and nutational movements could not possibly be as they are, if the planet consisted of a central core of molten rock surrounded with a crust of twenty or thirty miles in thickness; that the least possible thickness of crust consistent with the existing movements was from 800 to 1000 miles; and that the whole might even be solid to the centre, with the exception of comparatively small vesicular spaces filled with melted rock.[1]

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[1] But Lord Kelvin (Sir W. Thomson) has shown that if the rate of increase of temperature is taken to be 1° for every 51 feet for the first 100,000 feet, it will begin to diminish below that limit, being only 1° in 2550 feet at 800,000 feet, and then rapidly lessening. *Trans. Roy. Soc. Edin.* xxiii. p. 163.

[2] See D. Forbes, *Popular Science Review*, April, 1869.

M. Delaunay[2] threw doubt on Hopkins' views, and suggested that, if the interior were a mass of sufficient viscosity, it might behave as if it were a solid, and thus the phenomena of precession and nutation might not be affected. Lord Kelvin (Sir W. Thomson), who had already arrived at the conclusion that the interior of the globe must be solid, and acquiesced generally in Hopkins' conclusions, remarked that the hypothesis of a viscous and quasi-rigid interior "breaks down when tested by a simple calculation of the amount of tangential force required to give to any globular portion of the interior mass the precessional and nutational motions which, with other physical astronomers, M. Delaunay attributes to the earth as a whole."[3] He held the earth's crust down to depths of hundreds of kilometres to be capable of resisting such a tangential stress (amounting to nearly $\frac{1}{10}$th of a gramme weight per square centimetre) as would with great rapidity draw out of shape any plastic substance which could properly be termed a viscous fluid, and he concluded "that the rigidity of the earth's interior substance could not be less than a millionth of the rigidity of glass without very sensibly augmenting the lunar nineteen-yearly nutation."[4]

In Hopkins' hypothesis he assumed the crust to be infinitely rigid and unyielding, which is not true of any material substance. Lord Kelvin subsequently returning to the problem, in the light of his own researches in vortex-motion, found that, while the argument against a thin crust and vast liquid interior is still invincible, the phenomena of precession and nutation do not decisively settle the question of internal fluidity, as Hopkins, and others following him, had believed, though the solar semi-annual and lunar fortnightly nutations absolutely disprove the existence of a thin rigid shell full of liquid. If the inner surface of the crust or shell were rigorously spherical, the interior mass of supposed liquid could experience no precessional or nutational influence, except in so far as, if heterogeneous in composition, it might suffer from external attraction due to non-sphericity of its surfaces of equal density. But "a very slight deviation of the inner surface of the shell from perfect sphericity would suffice, in virtue of the quasi-rigidity due to vortex-motion, to hold back the shell from taking sensibly more precession than it would give to the liquid, and to cause the liquid (homogeneous or heterogeneous) and the shell to have sensibly the same precessional motion as if the whole constituted one rigid body."[1] The problem presented by the precession of a viscous spheroid has more recently been discussed by Professor George Darwin, who arrives at results nearly the same as those announced by Lord Kelvin regarding the slight difference between the precession of a fluid and a rigid spheroid.[2]

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[1] *Phil. Trans.* 1839, p. 381; 1840, p 193; 1842, p. 43; *Brit. Assoc.* 1847.

[2] In a paper on the hypothesis of the interior fluidity of the globe, *Comptes rendus*, July 13, 1868. *Geol. Mag.* v. p. 507. See also H. Hennessy, *Comptes rendus*, 6 March, 1871, *Geol. Mag.* viii. p. 216. *Nature*, xv. p. 78. O. Fisher, 'Physics of the Earth's Crust,' 2nd Edition, 1889.

[3] *Nature*, February 1, 1872.

[4] *Loc. cit.* p. 258.

The assumption of a comparatively thin crust requires that the crust shall have such perfect rigidity as is possessed by no known substance. The tide-producing force of the moon and sun exerts such a strain upon the substance of the globe, that it seems in the highest degree improbable that the planet could maintain its shape as it does unless the supposed crust were at least 2000 or 2500 miles in thickness.[3] That the solid mass of the earth must yield to this strain is certain, though the amount of deformation is so slight as to have hitherto escaped all attempts to detect it.[4] Had the rigidity been even that of glass or of steel, the deformation would probably have been by this time detected, and the actual phenomena of precession and nutation, as well as of the tides, would then have been very sensibly diminished.[5] The conclusion is thus reached that the mass of the earth "is on the whole more rigid certainly than a continuous solid globe of glass of the same diameter."[6]

(*b*.) Argument from the tides.—The phenomena of the oceanic tides show that the earth acts as a rigid body either solid to the centre, or possessing so thick a crust (2500 miles or more) as to give to the planet practical solidity. Lord Kelvin remarks that "were the crust of continuous steel and 500 kilometres thick, it would yield very nearly as much as if it were india-rubber to the deforming influences of centrifugal force, and of the sun's and moon's attractions." It would yield, indeed, so freely to these attractions "that it would simply carry the waters of the ocean up and down with it, and there would be no sensible tidal rise and fall of water relatively to land."[7] Prof. G. H. Darwin, in the series of papers already referred to, has investigated mathematically the bodily tides of viscous and semi-elastic spheroids, and the character of the ocean tides on a yielding nucleus.[8] His results tend to increase the force of Sir William Thomson's argument, since they show that "no very considerable portion of the interior of the earth can even distantly approach the fluid condition," the effective rigidity of the whole globe being very great.

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[1] Lord Kelvin (Sir W. Thomson), *Brit. Assoc. Rep.* 1876, Sections, p. 5.

[2] *Phil. Trans.* 1879, Part 2, p. 464.

[3] Lord Kelvin, *Proc. Roy. Soc.* April, 1862.

[4] See *Association Française pour l'Avancement des Sciences*, v. p. 281.

[5] Lord Kelvin, *loc. cit.*

[6] *Ibid. Trans. Roy. Soc. Edin.* xxiii. p. 157.

[7] *Ibid. Brit. Assoc. Rep.* 1876, Sections, p. 7.

[8] *Phil. Trans.* 1879, Part 2. See also *Brit. Assoc. Rep.* 1882, Sects. p. 473.

(*c*.) Argument from relative densities of melted and solid rock.—The two preceding arguments must be considered decisive against the hypothesis of a thin shell or crust covering a nucleus of molten matter. It has been further urged, as an objection to this hypothesis, that cold solid rock is more dense than hot melted rock, and that even if a thin crust were formed over the central molten globe it would immediately break up and the fragments would sink towards the centre.[1] Recent experiments show that diabase (of density 3·017) contracts nearly 4 per cent on solidification, and that the resulting homogeneous glass has a density of only 2·717.[2] As has been already pointed out, the specific gravity of the interior is at least twice as much as that of the visible parts of the crust. If this difference be due, not merely to the effect of pressure, but to the presence in the interior of intensely heated metallic substances, we cannot suppose that solidified portions of such rocks as granite and the various lavas could ever have sunk into the centre of the earth, so as to build up there the honey-combed cavernous mass which might have served as a nucleus in the ultimate solidification of the whole planet. If the earliest formed portions of the comparatively light crust were denser than the underlying liquid, they would no doubt descend until they reached a stratum with specific gravity agreeing with their own, or until they were again melted.[3]

3. *Hypothesis of a liquid substratum between a solid nucleus and the crust.*—Since the early and natural belief in the liquidity of the earth's interior has been so weightily opposed by physical arguments, geologists have endeavoured to modify it in such a way as, if possible, to satisfy the requirements of physics, while at the same time providing an adequate explanation of the corrugation of the earth's crust, the phenomena of volcanoes, &c.[4] The hypothesis has been proposed of "a rigid nucleus nearly approaching the size of the whole globe, covered by a fluid substratum of no great thickness, compared with the radius, upon which a crust of lesser density floats in a state of equilibrium." The nucleus is assumed to owe its solidity to "the enormous pressure of the superincumbent matter, while the crust owes its solidity to having become cool. The fluid substratum is not under sufficient pressure to be

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[1] This objection has been repeatedly urged by Lord Kelvin. See *Trans. Roy. Soc. Edin.* xxiii. p. 157; and *Brit. Assoc. Rep.* 1870, Sections, p. 7.

[2] C. Barus, *Phil. Mag.* 1893, p. 174. It is nevertheless true that, from a cause merely mechanical, pieces of the original cold rock, though so much denser, will float for a time on the melted material. *Ib.* p. 189.

[3] See D. Forbes, *Geol. Mag.* vol. iv. p. 435. The evidence for the internal solidity of the earth is criticised by Dr. M. E. Wadsworth in the *American Naturalist*, 1884.

[4] See Dana in *Silliman's Journal*, iii. (1847), p. 147. *Amer. Journ. Science* (1873). The hypothesis of a fluid substratum has been advocated by Shaler. *Proc. Bost. Nat. Hist. Soc.* xi. (1868), p. 8. *Geol. Mag.* v. p. 511. J. Le Conte, *Amer. Journ. Sci.* 1872, 1873. O. Fisher, *Geol. Mag.* v. (new series), pp. 291 and 551. 'Physics of the Earth's Crust,' 1883. [This author in his second edition modifies this view.] Hill, *Geol. Mag.* v. (new series), pp. 262, 479. The idea of a viscous layer between the solidifying central mass and the crust was present in Hopkins' mind. *Brit. Assoc.* 1848, Reports, p. 48.

rendered solid, and is sufficiently hot to be fluid, being probably more viscous in its lower portion through pressure and likewise passing into a viscous state in its upper parts through cooling, until it joins the crust."[1] The contraction and consolidation of this substratum are assumed as the explanation of the plication which the crust has certainly undergone.

It must be admitted that the wide-spread proofs of great crumpling of the rocks of the crust present a difficulty, for they indicate a capability of yielding to strain such as has been supposed impossible in a globe possessing on the whole the rigidity of steel or glass. But this difficulty may be more formidable in appearance than in reality. The earth must certainly possess such a degree of rigidity as to resist tidal deformation. Professor Darwin has calculated the limiting rigidity in the materials of the earth which is necessary to prevent the weight of mountains and continents from reducing them to the fluid condition or else cracking, and has found that these materials must be as strong as granite 1000 miles below the surface, or else much stronger than granite near the surface.[2] But high rigidity, that is, elasticity of form, is not contradictory of plasticity. Even bodies like steel may, under suitable stress, be made to flow like butter (see *postea*, Book III. Part I. Sect. iv. § 3). While, therefore, the earth may possess as a whole the rigidity of steel, there seems no reason why, under sufficient strain, the outer portions may not be plicated or even reduced to the fluid condition. It is important "to distinguish viscosity, in which flow is caused by infinitesimal forces, from plasticity, in which permanent distortion or flow only sets in when the stresses exceed a certain limit."[3]

In speculating on the plication of the earth's crust, we ought not to forget that, from the earliest times, the existing continental regions seem to have specially suffered from the efforts of the planet to adjust its external form to its diminishing diameter and lessening rapidity of rotation. They have served as lines of relief from the strain of compression during many successive epochs. It is along their axial lines,—their long dominant mountain-ranges, that we should naturally look for evidence of corrugation. Away from these lines of weakness the ground has been upraised for thousands of square miles without plication of the rocks, as in the instructive region of the Western Territories of North America. Nor is there any proof that corrugation takes place beneath the great oceanic areas of subsidence.

It appears highly probable that the substance of the earth's interior is at the melting-point proper for the pressure at each depth. Any relief from pressure, therefore, may allow of the liquefaction of the matter so relieved. Such relief is doubtless afforded by the corrugation of mountain-chains and other terrestrial ridges. And it is in these lines of uprise that volcanoes and other manifestations of subterranean heat actually show themselves.

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[1] Fisher, 'Physics of Earth's Crust,' 1st edit. p. 269.

[2] *Proc. Roy. Soc.* 1881, p. 432.

[3] Professor Darwin in a letter to the author, 9th January, 1884.

§ 4. **Age of the Earth and Measures of Geological Time.**—The age of our planet is a problem which may be attacked either from the geological or physical side.

1. The geological arguments rest chiefly upon the observed rates at which geological changes are being effected at the present time, and is open to the obvious preliminary objection that it assumes the existing rate of change as the measure of past revolutions,—an assumption, however, which may be erroneous, for the present may be a period when all geological events march forward more slowly than they used to do. The argument proceeds on data partly of a physical and partly of an organic kind. (*a.*) The physical evidence is derived from such facts as the observed rates at which the surface of a country is lowered by rain and streams, and new sedimentary deposits are formed. These facts will be more particularly dwelt upon in later sections of this volume. If we assume that the land has been worn away, and that stratified deposits have been laid down, nearly at the same rate as at present, then we must admit that the stratified portion of the crust of the earth must represent a very vast period of time.[1] (*b.*) On the other hand, human experience, so far as it goes, warrants the belief that changes in the organic world proceed with extreme slowness. Yet in the stratified rocks of the terrestrial crust, we have abundant proof that the whole fauna and flora of the earth's surface have passed through numerous cycles of revolution,—species, genera, families, orders, appearing and disappearing many times in succession. On any supposition, it must be admitted that these vicissitudes in the organic world can only have been effected with the lapse of vast periods of time, though no reliable standard seems to be available whereby these periods are to be measured. The argument from geological evidence indicates an interval of probably not much less than 100 million years since the earliest forms of life appeared upon the earth, and the oldest stratified rocks began to be laid down.

2. The physical argument as to the age of our planet is based by Lord Kelvin upon three kinds of evidence:—(1) the internal heat and rate of cooling of the earth; (2) the tidal retardation of the earth rotation; and (3) the origin and age of the sun's heat.

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[1] Dr. Croll put this period at not less, but possibly much more, than 60 million years. Dr. Haughton gives a much more extended period. Estimating the present rate of deposit of strata at 1 foot in 8616 years, assuming the former rate to have been ten times more rapid, or 1 foot in 861·6 years, and taking the thickness of the stratified rocks of the earth's crust at 177,200 feet, he obtains a minimum of 200,000,000 years for the whole duration of geological time: 'Six Lectures on Physical Geography,' 1880, p. 94. Dr. Haughton has also proposed another geological measure of past time, based upon the assumed effects of continental upheaval (*Proc. Roy. Soc.* xxvi. (1877), p. 534). But Professor Darwin has shown it to be inadmissible. (*Op. cit.* xxvii. (1878), p. 179.) For various opinions regarding geological measures of time see J. Phillips, *Brit. Assoc.* 1864: Croll, *Phil. Mag.* 1868: T. M'K. Hughes, *Proc. Roy. Inst. Great Britain*, March 24, 1876: Dupont, *Bull. Acad. Roy. Belgique*, viii. (1884): T. Mellard Reade, *Quart. Journ. Geol. Soc.* 1888, p. 291.

(1.) Applying Fourier's theory of thermal conductivity, he pointed out as far back as the year 1862, that in the known rate of increase of temperature downward beneath the surface, and the rate of loss of heat from the earth, we have a limit to the antiquity of the planet. He showed, from the data available at the time, that the superficial consolidation of the globe could not have occurred less than 20 million years ago, or the underground heat would have been greater than it is; nor more than 400 million years ago, otherwise the underground temperature would have shown no sensible increase downwards. He admitted that very wide limits were necessary. In subsequently discussing the subject, he inclined rather towards the lower than the higher antiquity, but concluded that the limit, from a consideration of all the evidence, must be placed within some such period of past time as 100 millions of years. He would now restrict the time to about 20 millions.[1]

(2.) The reasoning from tidal retardation proceeds on the admitted fact that, owing to the friction of the tide-wave, the rotation of the earth is retarded, and is therefore slower now than it must have been at one time. Lord Kelvin contends that had the globe become solid some 10,000 million years ago, or indeed any high antiquity beyond 100 million years, the centrifugal force due to the more rapid rotation must have given the planet a very much greater polar flattening than it actually possesses. He admits, however, that though 100 million years ago that force must have been about 3 per cent greater than now, yet "nothing we know regarding the figure of the earth and the disposition of land and water would justify us in saying that a body consolidated when there was more centrifugal force by 3 per cent than now, might not now be in all respects like the earth, so far as we know it at present."[2]

(3.) The third kind of evidence leads to results similar to those derived from the two previous lines of reasoning. It is based upon calculations as to the amount of heat that would be available by the falling together of masses from space, which gave rise by their impact to our sun, and the rate at which this heat has been radiated. Assuming that the sun has been cooling at a uniform rate, Professor Tait concludes that it cannot have supplied the earth, even at the present rate, for more than about 15 or 20 million years.[3] Lord Kelvin also believes that the sun's light will not last more than 5 or 6 millions of years longer.[4]

There can be no doubt that the demands of the earlier geologists for an unlimited duration of past time, for the accomplishment of geological history, were extravagant and unnecessary. But it may be questioned how far the recent limitation of time proposed from physical considerations are really founded on well-established facts. The argument from the geological record in favour of a much longer period than physicists are disposed to concede is so strong that one is inclined to believe that these writers have overstated their case. The evidence from the nature of the sedimentary rocks, and from the succession of organic remains in these rocks, appears to me to demand an amount of time not far short of the hundred millions of years originally granted by Lord Kelvin.[1]

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[1] *Trans. Roy. Soc. Edin.* xxiii. p. 157. *Trans. Geol. Soc. Glasgow*, iii. p. 25. 'Popular Lectures and Addresses,' 2nd edit. (1891), p. 397. Professor Tait reduces the period to 10 or 15 millions. 'Recent Advances in Physical Science,' p. 167.

[2] *Trans. Geol. Soc. Glasgow*, iii. p. 16. Professor Tait, in repeating this argument concludes that, taken in connection with the previous one, "it probably reduces the possible period which can be allowed to geologists to something less than 10 millions of years." 'Recent Advances,' p. 174. Compare Newcomb, 'Popular Astronomy,' p. 505.

[3] *Op. cit.* p. 174.

[4] 'Popular Lectures, etc.,' p. 397.

PART II.—AN ACCOUNT OF THE COMPOSITION OF THE EARTH'S CRUST—MINERALS AND ROCKS.

The earth's crust is composed of mineral matter in various aggregates included under the general term Rock. A rock may be defined as a mass of matter composed of one or more simple minerals, having usually a variable chemical composition, with no necessarily symmetrical external form, and ranging in cohesion from mere loose débris up to the most compact stone. Granite, lava, sandstone, limestone, gravel, sand, mud, soil, marl and peat, are all recognised in a geological sense as rocks. The study of rocks is known as Lithology, Petrography or Petrology.

It will be most convenient to treat—1st, of the general chemical constitution of the crust; 2nd, of the minerals of which rocks mainly consist; 3rd, of the methods employed for the determination of rocks; 4th, of the external characters of rocks, 5th, of the internal texture and structure of rocks; 6th, of the classification of rocks; and 7th, of the more important rocks occurring as constituents of the earth's crust.

§ i. General Chemical Constitution of the Crust.

Direct acquaintance with the chemical constitution of the globe must obviously be limited to that of the crust, though by inference we may eventually reach highly probable conclusions regarding the constitution of the interior. Chemical research has discovered that some sixty-four[2] simple or as yet undecomposable bodies, called elements, in various proportions and compounds, constitute the accessible part of the crust. Of these, however, the great majority are comparatively of rare occurrence. The crust, so far as we can examine it, is mainly built up of about sixteen elements, which may be arranged in the two following groups, the most abundant bodies being placed first in each list:—

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[1] I have touched on this question in my Presidential Address to the British Association 1892. But see a paper by Mr. Clarence King, *Amer. Journ. Sci.* xlv. (1893).

[2] This number has within the last few years been increased by the alleged discovery of no fewer than fourteen new metals. Some of these bodies, however, have not yet been satisfactorily proved to be new. T. S. Humpidge, *Nature*, xxii. p. 232.

Metalloids.	Atomic Weight.	*Metals.*	Atomic Weight.
Oxygen	15·96	Aluminium	27·30
Silicon	28·00	Calcium	39·90
Carbon	11·97	Magnesium	23·94
Sulphur	31·98	Potassium	39·04
Hydrogen	1·00	Sodium	22·99
Chlorine	35·37	Iron	55·90
Phosphorus	30·96	Manganese	54·80
Fluorine	19·10	Barium	136·80

The sixteen elements here mentioned form about ~~ninety-nine parts~~ of the earth's crust; the other elements constitute only about a hundredth part, though they include gold, silver, copper, tin, lead, and the other useful metals, iron excepted. By far the most abundant and important element is Oxygen. It forms about 23 per cent by weight of air, 88·87 per cent of water, and about a half of all the rocks which compose the visible portion or crust of the globe. Another metalloid, Silicon, always united with oxygen, ranks next in abundance as a constituent of the crust. Of the remaining metalloids, Carbon and Sulphur sometimes occur in the free state, but more usually in combination. Chlorine (save perhaps at volcanic vents) does not occur in a free state, but is abundant in combination with the alkalies, especially with sodium. Fluorine is always found in combination, and has only recently been isolated by artificial chemical processes. It is the only element which has not been combined with oxygen. It chiefly occurs in union with Calcium as the mineral fluor-spar, and constitutes more than half of the ~~mineral~~ cryolite; but traces of its presence have been detected in other minerals, in sea-water, and in the bones, teeth, blood and milk of mammalia. Hydrogen occurs chiefly in combination with oxygen as the oxide, water, of which it forms 11·13 per cent by weight; also in combination with carbon as the hydrocarbons (mineral oils and gases), produced by the slow decomposition of organic matter. Phosphorus occurs with oxygen principally in calcic phosphate. Of the metals, a few are found in the native state (gold, silver, copper, &c.), but those of importance in the framework of the earth's crust have entered into combination with metalloids or with each other. Putting the more important metals and metalloids together, we may compute that oxygen, silicon, aluminium, magnesium, calcium, potassium, sodium, iron and carbon, form together more than 97 per cent of the whole known crust.

So far as accessible to observation, the outer portion of our planet consists mainly of metalloids. Its metallic constituents have already in great part entered into combination with oxygen, so that the atmosphere contains the residue of that gas which has not yet united itself to terrestrial compounds. In a broad view of the arrangement of the chemical elements in the external crust, the suggestive speculation of Durocher deserves attention.[1] He regarded all rocks as referable to two layers or magmas co-existing in the earth's crust, the one beneath the other, according to their specific gravities. The upper or outer shell, which he termed the acid or siliceous magma, contains an excess of silica, and has a mean density of 2·65. The lower or inner shell, which he called the basic magma, has from six to eight times more of the earthy bases and iron-oxides, with a mean density of 2·96. To the former he assigned the early plutonic rocks, granite, felsite, &c., with the more recent trachytes; to the latter he relegated all the heavy lavas, basalts, diorites, &c. The ratio of silica is 7 in the acid magma to 5 in the basic. Though the proportion of silicic acid or of the earthy and metallic bases cannot be regarded as any certain evidence of the geological date of rocks, nor of their probable depth of origin, it is nevertheless a fact that (with many important exceptions) the eruptive rocks of the older geological periods are very generally super-silicated and of lower specific gravity, while those of later time are very frequently poor in silica, but rich in the earthy bases and in iron and manganese, with a consequent higher specific gravity. The latter, according to Durocher, have been forced up from a lower zone through the lighter siliceous crust. The sequence of volcanic rocks, as first announced by Richthofen, has an interesting connection with this speculation.[1]

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[1] *Ann. des Mines*, 1857. Translated by Haughton, 'Manual of Geology,' 1866, p. 16.

The main mass of the earth's crust is composed of a few predominant compounds. Of these in every respect the most abundant and important is Silicon-dioxide or Silica (Kieselerde) SiO_2. As the fundamental ingredient of the mineral kingdom, it forms more than one half of the known crust, which it seems to bind firmly together, entering as a main ingredient into the composition of most crystalline and fragmental rocks as well as into the veins that traverse them. It occurs in the free state as the abundant rock-forming mineral quartz, which strongly resists ordinary decay, and is therefore a marked constituent of many of the more enduring kinds of rock. As one of the acid-forming oxides (H_4SiO_4, Silicic acid, Kieselsäure) it forms combinations with alkaline, earthy, and metallic bases, which appear as the prolific and universally diffused family of the silicates. Moreover, it is present in solution in terrestrial and oceanic waters, from which it is deposited in pores and fissures of rocks. It is likewise secreted from these waters by abundantly diffused species of plants and animals (diatoms, radiolarians, &c.) It has been largely effective in replacing the organic textures of former organisms, and thus preserving them as fossils.

Alumina or aluminium-oxide (Thonerde), Al_2O_3, occurs sparingly as corundum, which, however, according to F. A. Genth, was the original condition of many now abundant complex aluminous minerals and rocks. The most common condition of aluminium is in union with silica. In this form it constitutes the basis of the vast family of the aluminous silicates, of which so large a portion of the crystalline and fragmental rocks consists. Exposed to the atmosphere, these silicates lose some of their more soluble ingredients, and the remainder forms an earth or clay consisting chiefly of silicate of aluminium.

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[1] *Postea*, Book III. Part I. Section i. § 5.

Carbon is the fundamental element of organic life. In combination with hydrogen, as well as with oxygen, nitrogen and sulphur, it forms the various kinds of coal, and thus takes rank as an important rock-forming element. As carbon-dioxide, CO_2, it is present in the air, in rain, in the sea and in ordinary terrestrial waters. This oxide is soluble in water,[1] giving rise then to a dibasic acid termed Carbonic Acid (Kohlensäure), $CO(OH)_2$ or H_2CO_3, which forms carbonates, its combination with calcium having been instrumental in the formation of vast masses of solid rock. Carbon-dioxide constitutes a fifth part of the weight of ordinary limestone.

Sulphur (Soufre, Schwefel) occurs uncombined in occasional deposits like those of Sicily and Naples, to be afterwards described, also in union with iron and other metals as sulphides; but its principal condition as a rock-builder is in combination with oxygen as sulphuric acid (Schwefelsäure) H_2SO_4, which forms sulphates of lime, magnesia, &c.

Calcium enters into the composition of many crystalline rocks in combination with silica and with other silicates. But its most abundant form is in union with carbon-dioxide, when it appears as the mineral, calcite ($CaCO_3$), or the rock, limestone. Calcium-carbonate, being soluble in water containing carbonic acid, is one of the most universally diffused mineral ingredients of natural waters. It supplies the varied tribes of mollusks, corals, and many other invertebrates with mineral substance for the secretion of their tests and skeletons. Such too has been its office from remote geological periods, as is shown by the vast masses of organically-formed limestone, which enter so conspicuously into the structure of the continents. In combination with sulphuric acid, calcium forms important beds of gypsum and anhydrite.

Magnesium, Potassium, and Sodium play a less conspicuous but still essential part in the composition of the earth's crust. Magnesium, in combination with silica, forms a class of silicates of prime importance in the composition of volcanic and metamorphic rocks. As a carbonate, it unites with calcium-carbonate to form the widely diffused rock, dolomite. In union with chlorine, it takes a prominent place among the salts of sea-water. Potassium or Sodium, combined with silica, is present in small quantity in most silicates. In union with chlorine, as common salt, sodium is the most important mineral ingredient of sea-water, and can be detected in minute quantities in air, rain, and in terrestrial waters. In the old chemical formulæ hitherto employed in mineralogy the metals of the alkalies and alkaline earths are represented as oxides. Thus lime (calcium-monoxide), soda (sodium-monoxide), potash (potassium-monoxide), magnesia (magnesium-oxide), are denoted as in union with carbonic acid, sulphuric acid, silica, &c., forming carbonates, sulphates, silicates of lime, soda, &c.

Iron and Manganese are the two most common heavy metals, occurring both in the form of ores, and as constituents of rocks. Iron is the great pigment of nature. Its peroxide or sesquioxide, now known as ferric oxide, forms large mineral masses, and together with the protoxide or ferrous oxide, occurs in smaller or larger proportions in the great majority of crystalline rocks. Iron (as sulphate or in combination with organic acids) is removed in solution in the water of springs, and precipitated as a hydrous peroxide. Manganese is commonly associated with iron in minute proportions in igneous rocks, and being similarly removed in solution in water, is thrown down as bog manganese or wad.

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[1] One volume of water at 0° C. dissolves 1·7967 volumes of carbon-dioxide; at 15° C. the amount is reduced to 1·0020 volumes.

Silicic Acid, Carbonic Acid, and Sulphuric Acid are the three acids with which most of the bases that compose the earth's crust have been combined. With these we may connect the water which, besides merely percolating through rocks, or existing enclosed in the vesicles of minerals, has been chemically absorbed in the process of hydration, and which thus constitutes more than 10 or even 20 per cent of some rocks (gypsum).

Chemical analysis has revealed the numerous combinations in which the elements are united to form minerals and rocks. Considerable additional light has been thrown on the subject by chemical synthesis, that is, by artificially producing the minerals and rocks which are found in nature. The experiments have been varied indefinitely so as to imitate as far as possible the natural conditions of production. Further reference to this subject will be found on pp. 89, 297 *et seq.*

Although every mineral may be made to yield data of more or less geological significance, only those minerals need be referred to here which enter as chief ingredients into the composition of rock-masses, or which are of frequent occurrence as accessories, and special note may be taken of those of their characters which are of main interest from a geological point of view, such as their modes of occurrence in relation to the genesis of rocks, and their weathering as indicative of the nature of rock-decomposition.

§ ii. Rock-forming Minerals.

Minerals, as constituents of rocks, occur in four conditions, according to the circumstances under which they have been produced.

(1.) *Crystalline*, as (*a*) more or less regularly defined crystals, which, exhibiting the outlines proper to the mineral to which they belong, are said to be *idiomorphic*; (*b*) amorphous granules, aggregations or crystalloids, having an internal crystalline structure, in most cases easily recognisable with polarized light, as in the quartz of granite, and an external form which has been determined by contact with the adjacent mineral particles; such crystalline bodies which do not exhibit their proper crystalline outlines are said to be *allotriomorphic*; (*c*) "crystallites" or "microlites," incipient forms of crystallization, which are described on p. 115. The crystalline condition may arise from igneous fusion, aqueous solution, or sublimation.[1]

(2.) *Glassy* or *vitreous*, as a natural glass, usually including either crystals or crystallites, or both. Minerals have assumed this condition from a state of fusion, also from solution. The glass may consist of several minerals fused into one homogeneous substance. Where it has assumed a lithoid or stony structure, these component minerals crystallize out of the glassy magma, and may be recognised in various stages of growth (*postea*, pp. 109-121).

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[1] For the microscopic characters of minerals and rocks, see p. 108.

(3.) *Colloid*, as a jelly-like though stony substance, deposited from aqueous solution. The most abundant mineral in nature which takes the colloid form is silica. Opal is a hardened colloidal condition of this substance. Chalcedony, doubtless originally colloidal silica, now unites the characters of quartz and opal, being only partially soluble in caustic potash and partially converted into a finely fibrous, doubly-refracting substance.

(4.) *Amorphous*, having no crystalline structure or form, and occurring in indefinite masses, granules, streaks, tufts, stainings, or other irregular modes of occurrence.

A mineral which has replaced another and has assumed the external form of the mineral so replaced, is termed a *Pseudomorph*. A mineral which encloses another has been called a *Perimorph*; one enclosed within another, an *Endomorph*.

Essential or accessory, original or secondary minerals.—A mineral is an essential ingredient when its absence would so alter the character of a rock as to make it something fundamentally different. The quartz of granite, for example, is an essential constituent of that rock, the removal of which would alter the petrographical species. A mineral is said to be accessory when its absence would not change the essential character of the rock. All essential minerals are original constituents of a rock, but all the original constituents are not essential. In granite, such minerals as topaz, beryl, and sphene often occur under circumstances which show that they crystallized out of the original magma of the rock. But they form so trifling a proportion in the total mass, and their absence would so little affect the general character of that mass, that they are regarded as accessory, though undoubtedly original and often important ingredients.[1] Again, in rocks of eruptive origin, the essential ingredients cannot be traced back further than the eruption of the mass containing them. They are not only original, as constituents of the lava, but are themselves original and non-derivative minerals, produced directly from the crystallization of molten minerals ejected from beneath the earth's crust, though, as Michel-Lévy has shown, the débris of older minerals may sometimes be traced amidst the later crystals of massive rocks.[2] In rocks of aqueous origin, however, there are many, such as conglomerates and sandstones, where the component minerals, though original ingredients of the rocks, are evidently of derivative origin. The little quartz-granules of a sandstone have formed part of the rock ever since it was accumulated, and are its essential constituents. Yet each of these once formed part of some older rock, the destruction of which yielded materials for the production of the sandstone. The minute crystals of zircon, rutile, tourmaline and other minerals so often found in sands, clays, sandstones, shales and other sedimentary deposits, have been derived from the degradation of older crystalline rocks.

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[1] Some of the "accessory" minerals may be of great importance as indicative of the conditions under which the rock was formed.

[2] *Bull. Soc. Géol. France*, 3rd ser. iii. 199. See also Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 189. Some eruptive rocks abound in corroded or somewhat rounded or broken crystals which obviously have belonged to some previous state of consolidation. Such crystals, which are obviously more ancient than those forming the general mass of the rock, have been called *allogenic*, while those which belong to the time of formation of the rock, or to some subsequent change within the rock, are known as *authigenic*.

The same mineral may occur both as an original and as a secondary constituent. Quartz, for example, appears everywhere in both conditions; indeed, it may sometimes be found in a twofold form even in the same rock, though there is then usually some difference between the original and secondary quartz. A quartz-felsite, for instance, abounds in original little kernels, or in double pyramids of the mineral, often enclosing fluid cavities, while the secondary or accidental forms usually occur in veins, reticulations, or other irregular aggregates.

Accessory minerals frequently occur in cavities where they have had some room to crystallize out from the general mass. The "drusy" cavities, or open spaces lined with well developed crystals, found in some granites are good examples, for it is there that the non-essential minerals are chiefly to be recognised. The veins of segregation found in many crystalline rocks, particularly in those of the granite series, are further illustrations of the original separation of mineral ingredients from the general magma of a rock (see pp. 578, 580).

In some cases minerals assume a concretionary shape, which may be observed chiefly though not entirely in rocks formed in water. Some minerals are particularly prone to occur in concretions. Siderite (ferrous carbonate) is to be found in abundant nodules, mixed with clay and organic matter among consolidated muddy deposits. Calcite (calcium-carbonate) is likewise abundantly concretionary. Silica in the forms of chert and flint appears in irregular concretions, in calcareous formations, composed mainly of the remains of marine organisms.

Secondary minerals have been developed as the result of subsequent changes in rocks, and are almost invariably due to the chemical action of percolating water, either from above or from below. Occurring under circumstances in which such water could act with effect, they are found in cracks, joints, fissures and other divisional planes and cavities of rocks, especially in the minute interspaces between the component grains or minerals. Subterranean channels, frequently several feet or even yards wide, have been gradually filled up by the deposit of mineral matter on their sides (see the Section on Mineral Veins). The cavities formed by expanding steam in ancient lavas (amygdaloids) have offered abundant opportunities for deposits of this kind, and have accordingly been in large measure occupied by secondary minerals (amygdales), as calcite, chalcedony, quartz and zeolites.

In the subjoined list of the more important rock-forming minerals, attention is drawn mainly to those features that are of geological importance; the physical, chemical and microscopic characters of these minerals will be found in a text-book of mineralogy or petrography.

Reference is therefore made here to features of more special significance to the geologist, such as modes of occurrence, whether original or secondary; modes of origin, whether igneous, aqueous, or organic; pseudomorphs, that is, the various minerals which any given mineral has replaced, while retaining their external forms, and likewise those which are found to have supplanted the mineral in question while in the same way retaining its form—a valuable clue to the internal chemical changes which rocks undergo from the action of percolating water (Book III. Part II. Section ii. §§ 1 and 2); and lastly, characteristics or peculiarities of weathering, where any such exist that deserve special mention.

1. NATIVE ELEMENTS are comparatively of rare occurrence, and only two of them, Carbon and Sulphur, occasionally play the part of noteworthy essential and accessory constituents of rocks. A few of the native metals, more especially copper and gold, now and then appear in sufficient quantity to constitute commercially important ingredients of veins and rock-masses.

Graphite is found chiefly in ancient crystalline rocks, as gneiss, mica-schist, granite, &c.; some of the Laurentian limestones of Canada being so full of the diffused mineral as to be profitably worked for it; in rare instances coal has been observed changed into it by intrusive basalt (Ayrshire). In some cases graphite results from the alteration of imbedded organic matter, especially remains of plants; but its presence, and that of diamond, among ancient crystalline rocks and in meteorites can hardly be thus accounted for. Occasionally it is observed as a pseudomorph after calcite and pyrites, and sometimes enclosing sphene and other minerals.[1]

Sulphur occurs 1st, as a product of volcanic action in the vents and fissures of active and dormant cones. Volcanic sulphur is formed from the oxidation of the sulphuretted hydrogen, so copiously emitted with the steam that issues from volcanic vents, as at the Solfatara, near Naples. It may also be produced by the mutual decomposition of the same gas and anhydrous sulphuric acid. 2nd, in beds and layers, or diffused particles, resulting from the alteration of previous minerals, particularly sulphates, or from deposit in water through decomposition of sulphuretted hydrogen. The frequent crystallization of sulphur shows that the mineral must have been formed at ordinary temperatures, for its natural crystals melt at 238·1° Fahr. Its formation may be observed in progress at many sulphureous springs, where it falls to the bottom as a pale mud through the oxidation of the sulphuretted hydrogen in the water. It occurs in Sicily, Spain and elsewhere, in beds of bituminous limestone and gypsum. These strata, sometimes full of remains of fresh-water shells and plants, are interlaminated with sulphur, the very shells being not infrequently replaced by this mineral. Here the presence of the sulphur may be traced to the reduction of the calcium-sulphate to the state of sulphide, through the action of the decomposing organic matter, and the subsequent production and decomposition of sulphuretted hydrogen, with consequent liberation of sulphur.[2] The sulphur deposits of Sicily furnish an excellent illustration of the alternate deposit of sulphur and limestone. They consist mainly of a marly limestone, through which the sulphur is partly disseminated and partly interstratified in thin laminæ and thicker layers, some of which are occasionally 28 feet deep. Below these deposits lie older Tertiary gypseous formations, the decomposition of which has probably produced the deposits of sulphur in the overlying more recent lake basins.[3] The weathering of sulphur is exemplified on a considerable scale at these Sicilian deposits. The mineral, in presence of limestone, oxygen and moisture, becomes sulphuric acid, which, combining with the limestone, forms gypsum, a curious return to what was probably the original substance from the decomposition of which the sulphur was derived. Hence the site of the outcrop of the sulphur beds is marked at the surface by a white earthy rock, or borscale, which is regarded by the miners in Sicily to be a sure indication of sulphur underneath, as the gossan of Cornwall is indicative of underlying metalliferous veins.[1]

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[1] Vom Rath. *Sitzungsber. Wien. Akad.* x. p. 67; Sullivan in Jukes' 'Manual of Geology,' 3rd edit. (1872), p. 56.

[2] Braun, *Bull. Soc. Géol. France*, 1st ser. xii. p. 171.

[3] *Memorie del R. Comitato Geologico d'Italia*, i. (1871).

Iron, the most important of all the metals, is found only sparingly in the native state, in blocks which have fallen as meteorites, also in grains or dust enclosed in hailstones, in snow of the Alps, Sweden and Siberia, in the mud of the ocean floor at remote distances from land, and in some eruptive rocks. There can be no doubt that a small but constant supply of native iron (cosmic dust) is falling upon the earth's surface from outside the terrestrial atmosphere.[2] This iron is alloyed with nickel, and contains small quantities of cobalt, copper and other ingredients. Dr. Andrews, however, showed in 1852 that native iron, in minute spicules or granules, exists in some basalts and other volcanic rocks,[3] and Mr. J. Y. Buchanan has detected it in appreciable quantity in the gabbro of the west of Scotland. It occurs also in the basalts of Bohemia and Greenland.[4]

In the great majority of cases the OXIDES occur combined with some acid. A few uncombined take a prominent place as essential constituents or frequent ingredients of rocks, especially the oxides of silicon and iron.

2. SILICA (SiO_2) is found in three chief forms, Quartz, Tridymite, and Opal.

Quartz is abundant as (1) an essential constituent of rocks, as in granite, gneiss, mica-schist, rhyolite (quartz-trachyte,) quartz-porphyry, sandstone; (2) a secondary ingredient, wholly or partially filling veins, joints, cracks, and cavities. It has been produced from (*a*) igneous action, as in volcanic rocks; (*b*) aquo-igneous or plutonic action, as in granites, gneisses, &c.; (*c*) solution in water, as where it lines cavities or replaces other minerals. The last mode of formation is that of the crystallized quartz and chalcedony found as secondary ingredients in rocks.

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[1] *Journ. Soc. Arts*, 1873, p. 170. E. Ledoux, *Ann. des Mines*, 7^me^ sér. vii. p. 1. The Sicilian sulphur beds belong to the Oeningen stage of the Upper Tertiary deposits. They contain numerous plants and some insects. H. T. Geyler, *Palæontographica*, xxiii., *Lief.* 9, p. 317. Von Lasaulx, *Neues Jahrb.* 1879, p. 490.

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[3] *Brit. Assoc. Rep.* 1852, *postea*, p. 457.

[4] Nordenskiöld describes fifteen blocks of iron on the island of Disco, Greenland, the weight of the two largest being 21,000 and 8000 kilogrammes (20 and 8 tons, respectively). He observed that at the same locality, the underlying basalt contains lenticular and disc-shaped blocks of precisely similar iron, and inferred that the whole of the blocks may belong to a meteoric shower which fell during the time (Tertiary) when the basalt was poured out at the surface. He dismissed the suggestion that the iron could possibly be of telluric origin (*Geol. Mag.* ix. (1872) p. 462). But the microscope reveals in this basalt the presence of minute particles of native iron which, associated with viridite, are moulded round the crystals of labradorite and augite (Fouqué and Michel-Lévy, *op. cit.* p. 443). Steenstrup, Daubrée, and others appear therefore to be justified in regarding this iron as derived from the inner metallic portions of the globe, which lie at depths inaccessible to our observations, but from which the vast Greenland basalt eruptions have brought up traces to the surface (K. J. T. Steenstrup, *Vid. Medd. Nat. Foren.* Copenhagen (1875) No. 16-19, p. 284; *Zeitsch. Deutsch. Geol. Ges.* xxviii. (1876) p. 225; *Mineralog. Mag.* July, 1884. F. Wöhler, *Neues Jahrb.* 1879, p. 832. Daubrée, *Discours Acad. Sci.* 1 March 1880, p. 17. W. Flight, *Geol. Mag.* ii. (2nd ser.) p. 152.

The study of the endomorphs and pseudomorphs of quartz is of great importance in the investigation of the history of rocks. No mineral is so conspicuous for the variety of other minerals enclosed within it. In some secondary quartz-crystals, each prism forms a small mineralogical cabinet enclosing a dozen or more distinct minerals, as rutile, hæmatite, limonite, pyrites, chlorite, and many others.[1] Quartz may be observed replacing calcite, aragonite, siderite, gypsum, rock-salt, hæmatite, &c. This facility of replacement makes silica one of the most valuable petrifying agents in nature. Organic bodies which have been silicified retain, often with the utmost perfection, their minutest and most delicate structures.

Quartz may usually be identified by its external characters, and especially by its vitreous lustre and hardness. When in the form of minute blebs or crystals, it may be recognised in many rocks with a good lens. Under the microscope, it presents a characteristic brilliant chromatic polarization, and in convergent light gives a black cross. Where it is an original and essential constituent of a rock, quartz very commonly contains minute rounded or irregular cavities or pores, partially filled with liquid. So minute are these cavities that a thousand millions of them may, when they are closely aggregated, lie within a cubic inch. The liquid is chiefly water, not uncommonly containing sodium chloride or other salt, sometimes liquid carbon-dioxide and hydrocarbons.[2] Chalcedony exhibits under the microscope a minute radial fibrous structure.

Rock-crystal and crystalline quartz resist atmospheric weathering with great persistence. Hence the quartz-grains may usually be easily discovered in the weathered crust of a quartziferous igneous rock. But corroded quartz-crystals have been observed in exposed mountainous situations, with their edges rounded and eaten away.[3] The chalcedonic and more or less soluble forms of silica are more easily affected. Flint and many forms of coloured chalcedony weather with a white crust. But it is chiefly from the weathering of silicates (especially through the action of organic acids) that the soluble silica of natural waters is derived. (Book III. Part II. Section ii. § 7).

Tridymite has been met with chiefly among volcanic rocks (trachytes, andesites, &c.), both as an abundant constituent of those which have been poured out in the form of lava, and also in ejected blocks (Vesuvius).[4]

Opal, a hydrous condition of silica formed from solution in water, is usually disseminated in veins and nests through rocks. Semi-opal occasionally replaces the original substance of fossil wood (wood-opal). Several forms of opal are deposited by geysers, and are known under the general appellation of sinters. Closely allied to the opals are the forms in which hydrous (soluble) silica appears in the organic world, where it constitutes the frustules of diatoms, the skeletons of radiolaria, &c. Tripoli powder (Kieselguhr), randanite, and other similar earths, are composed mainly or wholly of the remains of diatoms, &c.

Corundum, aluminium-oxide, is found in crystalline rocks, particularly in certain serpentines and schists, gneiss, granite, dolomite, and rocks of the metamorphic series.

3. IRON OXIDES.—Four minerals, composed mainly of iron oxides, occur abundantly

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as essential and accessory ingredients of rocks. Hæmatite, Limonite, Magnetite, and Titanic iron.

Hæmatite (Fer oligiste, Rotheisen, Eisenglanz, $Fe_2O_3 = Fe 70, O 30$) in the crystallized form occurs in veins, as well as lining cavities and fissures of rocks. The fibrous and more common form (which often has portions of its mass passing into the crystallized condition) lies likewise in strings or veins; also in cavities, which, when of large size, have given opportunity for the deposit of great masses of hæmatite, as in cavernous limestones (Westmoreland). It occurs with other ores and minerals as an abundant component of mineral veins, likewise in beds interstratified with sedimentary or schistose rocks. Scales and specks of opaque or clear bright red hæmatite, of frequent occurrence in the crystals of rocks, give them a reddish colour or peculiar lustre (perthite, stilbite). Hæmatite appears abundantly as a product of sublimation in clefts of volcanic cones and lava streams. It is probably in most cases a deposition from water, resulting from the alteration of some previous soluble combination of the metal, such as the oxidation of the sulphate, and occurs in veins and beds, and as the earthy pigment that gives a red colour to sandstones, clays and other rocks. It is found pseudomorphous after ferrous carbonate, and this has probably been the origin of beds of red ochre occasionally intercalated among stratified rocks. It likewise replaces calcite, dolomite, quartz, barytes, pyrites, magnetite, rock-salt, fluor-spar, &c.

Limonite (Brown iron-ore, $2Fe_2O_3 + 3H_2O = Fe_2O_3$ 85·56, H_2O 14·44) occurs in beds among stratified formations, and may be seen in the course of deposit, through the action of organic acids, on marsh-land (bog-iron-ore) and lake-bottoms. (Book IV. Part II. Section iii.) In the form of yellow ochre, it is precipitated from the waters of chalybeate springs containing green vitriol derived from the oxidation of iron-sulphides.[1] It is a common decomposition product in rocks containing iron among their constituents. It is thus always a secondary or derivative substance, resulting from chemical alteration. It is the usual pigment which gives tints of yellow, orange and brown to rocks. The pseudomorphous forms of limonite show to what a large extent combinations of iron are carried in solution through rocks. The mineral has been found replacing calcite, siderite, dolomite, hæmatite, magnetite, pyrite, marcasite, galena, blende, gypsum, barytes, fluor-spar, pyroxene, quartz, garnet, beryl, &c.

Magnetite (Fer oxydulé, Magneteisen, Fe_3O_4) occurs abundantly in some schists, in scattered octohedral crystals; in crystalline massive rocks like granite, in diffused grains or minute crystals; among some schists and gneisses (Norway and the eastern states of North America), in massive beds; in basalt and other volcanic rocks, as an essential constituent, in minute octohedral crystals, or in granules or crystallites. It is likewise found as a pseudomorphous secondary product, resulting from the alteration of some previous mineral, as olivine, hæmatite, pyrite, quartz, hornblende, augite, garnet and sphene. It occurs with hæmatite, &c., as a product of sublimation at volcanic foci, where chlorides of the metals in presence of steam are resolved into hydrochloric acid and anhydrous oxides. It may thus result from either aqueous or igneous operations. It is liable to weather by the reducing effects of decomposing organic matter, whereby it becomes a carbonate, and then by exposure passes into the hydrous or anhydrous peroxide. The magnetite grains of basalt-rocks are very generally oxidized at the surface, and sometimes even for some depth inward.

Titanic Iron (Titaniferous Iron, Menaccanite, Ilmenite, Fer titané, Titaneisen $(FeTi)_2O_3$) occurs in scattered grains, plates and crystals as an abundant constituent of many crystalline rocks (basalt-rocks, diabase, gabbro and other igneous masses); also in veins or beds in syenite, serpentine and metamorphic rocks;[2] scarcely to be distinguished from magnetite when seen in small particles under the microscope, but possessing a brown semi-metallic lustre with reflected light; resists corrosion by acids when the powder of a rock containing it is exposed to their action, while magnetite is attacked and dissolved. Titanic iron frequently resists weathering, so that its black glossy granules project from a weathered surface of rock. In other cases, it is decomposed either by oxidation of its protoxide, when the usual brown or yellowish colour of the hydrous ferric oxide appears, or by removal of the iron. The latter is believed to be the origin of a peculiar milky white opaque substance, frequently to be observed under the microscope, surrounding and even replacing crystals of titanic iron, and named Leucoxene by Gümbel.[1] In other cases the decomposition has resulted in the production of sphene.

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[1] Sullivan, Jukes' 'Manual of Geology,' p. 63.

[2] Some of the Canadian masses of this mineral are 90 feet thick and many yards in

Chromite ($FeCr_2O_4$) occurs in black opaque grains and crystals not infrequently in altered olivine-rocks.

Spinels, a group of minerals, may be taken here. They are closely related to each other, having cubic forms and varying in composition from *magnetite* (see above) at the one end to *spinel* ($MgAl_2O_4$) at the other. They are not infrequent as minute grains or crystals in some igneous and metamorphic rocks. Between magnetite and spinel come intermediate varieties, as *chromite* (see above), *Picotite*, *Hercynite* and *Pleonaste*.

4. MANGANESE OXIDES are frequently associated with those of iron in ordinary rock-forming minerals, but in such minute proportions as to have been generally neglected in analyses. Their presence in the rocks of a district is sometimes shown by deposits of the hydrous oxide in the forms of Psilomelane ($H_2MnO_4+H_2O$), and Wad ($MnO_2+MnO+H_2O$). These deposits sometimes take place as black or dark brown branching, plant-like or *dendritic* impressions between the divisional planes of close-grained rocks (limestone, felsite, &c.), sometimes as accumulations of a black or brown earthy substance in hollows of rocks, occasionally as deposits in marshy places, like those of bog-iron-ore, and abundantly on some parts of the sea-floor. (See p. 458.)

5. SILICATES.—These embrace by far the largest and most important series of rock-forming minerals. Their chief groups are the anhydrous aluminous and magnesian silicates embracing the Felspars, Hornblendes, Augites, Micas, &c., and the hydrous silicates which include the Zeolites, Clays, talc, chlorite, serpentine, &c.

The family of the Felspars forms one of the most important of all the constituents of rocks, seeing that its members constitute by much the largest portion of the plutonic and volcanic rocks, are abundantly present among many crystalline schists, and by their decay have supplied a great part of the clay out of which argillaceous sedimentary formations have been constructed.

The felspars are usually divided into two series. 1st, The orthoclastic or monoclinic felspars, consisting of two species or varieties, Orthoclase and Sanidine; and 2nd, The plagioclastic or triclinic felspars, among which, as constituents of rocks, may be mentioned the species albite, anorthite, oligoclase, andesine, labradorite, and microcline.

Orthoclase (K_2O 16·89, Al_2O_3 18·43, SiO_2 64·68) occurs abundantly as an original constituent of many crystalline rocks (granite, syenite, felsite, gneiss, &c.), likewise in cavities and veinings in which it has segregated from the surrounding mass (pegmatite); seldom found in unaltered sedimentary rocks except in fragments derived from old crystalline masses; generally associated with quartz, and often with hornblende, while the felspars less rich in silica more rarely accompany free quartz. It is an original constituent of plutonic and old volcanic rocks (granite, felsite, &c.), and of gneiss and various schists. A few examples have been noticed where it has replaced other minerals (prehnite, analcime, laumontite). Under the microscope it is recognisable from quartz by its characteristic rectangular forms, cleavage, twinning, angle of extinction, turbidity, and frequent alteration.[1] Orthoclase weathers on the whole with comparative rapidity, though durable varieties are known. The alkali and some of the silica are removed, and the mineral passes into clay or kaolin (p. 77).

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[1] 'Die Paläolitische Eruptivgesteine des Fichtelgebirges,' 1874, p. 29. See Rosenbusch, *Mik. Physiog.* ii. p. 336. De la Vallée Poussin and Renard, *Mém. Couronnées Acad. Roy. de Belgique*, 1876, xl. Plate vi. pp. 34 and 35. Fouqué and Michel-Lévy, 'Minéralogie Micrograph,' p. 426. See *postea*, p. 618.

Sanidine, the clear glassy fissured variety of orthoclase so conspicuous in the more silicated Tertiary and modern lavas, occurs in some trachytes in large flat tables (hence the name "sanidine"); more commonly in fine clear or grey crystals or crystalline granules; an eminently volcanic mineral.

Plagioclase (Triclinic) Felspars.—While the different felspars which crystallize in the triclinic system may be more or less easily distinguished in large crystals or crystalline aggregates, they are difficult to separate in the minute forms in which they commonly occur as rock constituents. They have been grouped by petrographers under the general name Plagioclase (with oblique cleavage), proposed by Tschermak, who regards them as mixtures in various proportions of two fundamental compounds—albite or soda-felspar, and anorthite or lime-felspar.

They occur mostly in well-developed crystals, partly in irregular crystalline grains, crystallites or microlites. On a fresh fracture, their crystals often appear as clear glassy strips, on which may usually be detected a fine parallel lineation or ruling, indicating a characteristic polysynthetic twinning which never appears in orthoclase. A felspar striated in this manner can thus be at once pronounced to be a triclinic form, though the distinction is not invariably present. Under the microscope, the fine parallel lamellation or striping, best seen with polarized light, forms one of the most distinctive features of this group of felspars. The chief triclinic felspars are, Microcline (potash-felspar, $K_2Al_2Si_6O_{16}$), which occurs in granites, particularly as the common felspar of the graphic varieties; also in some gneisses, &c.; Albite (soda-felspar, Na_2O, 11·82, Al_2O_3 18·56, Si_2O 68·62), found in some granites, and in several volcanic rocks; Oligoclase (soda-lime and lime-soda felspars, Na_2O 8·2, CaO 4·8, Al_2O_3 23·0, SiO_2 62·8) occurs in many granites and other eruptive rocks; Andesine (Na_2O 7·7, CaO 7·0, Al_2O_3 25·6, SiO_2 60·0) observed in some syenites, &c.; Labradorite (Na_2O 4·6, CaO 12·4, Al_2F_3 30·2, SiO_2 52·9), an essential constituent of many lavas, &c., abundant in masses in the azoic rocks of Canada, &c.; Anorthite (lime-felspar, CaO 20·10, Al_2O_3 36·82, SiO_2 43·08) found in many volcanic rocks, sometimes in granites and metamorphic rocks.

The triclinic felspars have been produced sometimes directly from igneous fusion, as can be studied in many lavas, where often one of the first minerals to appear in the devitrification of the original molten glass has been the labradorite or other plagioclase. In other cases, they have resulted from the operation of the processes to which the formation of the crystalline schists was due; large beds as well as abundant diffused strings, veinings, and crystals of triclinic felspar (labradorite) form a marked feature among the ancient gneisses of Eastern Canada. The more highly silicated species (albite, oligoclase) occur with orthoclase as essential constituents of many granites and other plutonic rocks. The more basic forms (labradorite, anorthite) are generally absent where free silica is present; but occur in the more basic igneous rocks (basalts, &c.)

Considerable differences are presented by the triclinic felspars in regard to weathering. On an exposed face of rock they lose their glassy lustre and become white and opaque. This change, as in orthoclase, arises from loss of bases and silica, and from hydration. Traces of carbonates may often be observed in weathered crystals. The original steam cavities of old volcanic rocks have generally been filled with infiltrated minerals, which in many cases have resulted from the weathering and decomposition of the triclinic felspars. Calcite, prehnite, and the family of zeolites have been abundantly produced in this way. The student will usually observe that where these minerals abound in the cells and crevices of a rock, the rock itself is for the most part proportionately decomposed, showing the relation that subsists between infiltration-products and the decomposition of the surrounding mass. Abundance of calcite in veins and cavities of a felspathic rock affords good ground for suspecting the presence in the latter of a lime felspar.[1] (See under "Albitization," *postea*, p. 618.)

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[1] On microscopic determination of felspars, see Fouqué and Michel-Lévy, *op. cit.* pp. 209, 227, and *postea*, pp. 94-96.

Saussurite, formerly described as a distinct mineral species, is now found to be the result of the decomposition of felspars, which have thus acquired a dull white aspect and contain secondary crystallizations (zoisite) out of the decomposed substance of the original felspar. Such saussuritic felspars occur in varieties of gabbro and diorite. Under the microscope they present a confused aggregate of crystalline needles and granules imbedded in an amorphous matrix. (See *postea*, p. 618.)

Leucite (K_2O 21·53, Al_2O_3 23·50, SiO_2 54·97) is a markedly volcanic mineral, occurring as an abundant constituent of many ancient and modern Italian lavas, and in some varieties of basalt. Under the microscope, sections of this mineral are eight-sided or nearly circular, and very commonly contain enclosures of magnetite, &c., conforming in arrangement to the external form of the crystal or disposed radially.

Nepheline (Na_2O 17·04, Al_2O_3 35·26, K_2O 6·46, SiO_2 41·24), essentially a volcanic mineral, being an abundant constituent of phonolite, of some Vesuvian lavas, and of some forms of basalt, presents under the microscope various six-sided and even four-sided forms, according to the angles at which the prisms are cut.[2] Under the name of *Elæolite* are comprised the greenish or reddish, dull, greasy-lustred, compact or massive varieties of nepheline, which occur in some syenites and other ancient crystalline rocks.

THE MICA FAMILY embraces a number of minerals, distinguished especially by their very perfect basal cleavage, whereby they can be split into remarkably thin elastic laminæ, and by a predominant splendent pearly lustre. They consist essentially of silicates of alumina, magnesia, iron and alkalies, and may be conveniently divided into two groups, the *white micas*, which are silicates of alumina with alkalies, iron and magnesia, and the *black micas*, in which the magnesia and iron play a more conspicuous part.

Muscovite (Potash-mica, white mica, Glimmer, K_2O 3·07–12·44, Na_2O 0–4·10, FeO 0–1·16, Fe_2O_3 0·46–8·80, MgO 0·37–3·08, Al_2O_3 28·05–38·41, SiO_2 43·47–51·73, H_2O 0·98–6·22), abundant as an original constituent of many crystalline rocks (granite, &c.), and as one of the characteristic minerals of the crystalline schists; also in many sandstones, where its small parallel flakes, derived, like the surrounding quartz grains, from older crystalline masses, impart a silvery or "micaceous" lustre and fissility to the stone.[3] The persistence of muscovite under exposure to weather is shown by the silvery plates of the mineral, which may be detected on a crumbling surface of granite or schist where most of the other minerals, save the quartz, have decayed; also by the frequency of the micaceous lamination of sandstones.

Biotite (Magnesia-mica, black mica, MgO 10–30 per cent) occurs abundantly as an original constituent of many granites, gneisses, and schists; also sometimes in basalt, trachyte, and as ejected fragments and crystals in tuff. Its small scales, when cut transverse to the dominant cleavage, may usually be detected under the microscope by their remarkably strong dichroism, their fine parallel lines of cleavage, and their frequently frayed appearance at the ends. Under the action of the weather it assumes a pale, dull, soft crust, owing to removal of its bases. The mineral *rubellan*, which occurs in hexagonal brown or red opaque inelastic tables in some basalts and other igneous rocks, is regarded as an altered form of biotite.

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[1] A valuable essay on the stages of the weathering of triclinic felspar as revealed by the microscope was published by G. Rose in 1867. *Zeitsch. Deutsch. Geol. Ges.* xix. p. 276.

[2] On the microscopic distinction between nepheline and apatite, see Fouqué and Michel-Lévy, 'Minéral. Micrograph.' p. 276.

[3] On the microscopic determination of the micas, see Fouqué and Michel-Lévy, *op. cit.* p. 333.

Phlogopite is another dark ferro-magnesian mica which contains a little fluorine. *Lepidolite* (Lithia-mica), occurs in some granites and crystalline schists, especially in veins. *Damourite*, merely a variety of muscovite, occurs among crystalline schists. *Sericite*, a talc-like variety of muscovite, occurs in soft inelastic scales in many schists, as a result of the alteration of orthoclase felspar.[1] *Margarodite*, a silvery talc-like hydrous mica, is widely diffused as a constituent of granite and other crystalline rocks. *Paragonite*, a scaly micaceous mineral, forms the main mass of certain alpine schists.

Hornblende (Monoclinic Amphibole, CaO_2 10–12, MgO 11–24, Fe_2O_3 0–10, Al_2O_3 5–18, SiO_2 40–50 also usually with some Na_2O, K_2O and FeO). Divided into two groups. 1st. Non-aluminous, including the white and pale green or grey fibrous varieties (tremolite, actinolite, &c.) 2nd. Aluminous, embracing the more abundant dark green, brown, or black varieties. Under the microscope, hornblende presents cleavage-angles of 124° 30′, the definite cleavage-planes intersecting each other in a well-marked lattice work, sometimes with a finely fibrous character superadded. It also shows a marked pleochroism with polarized light, which, as Tschermak first pointed out, usually distinguishes it from augite.[2] Hornblende has abundantly resulted from the alteration (paramorphism) of augite (see below, Uralite). In many rocks the ferro-magnesian silicate which is now hornblende was originally augite; the epidiorites, for instance, were probably once dolerites or allied pyroxenic rocks. The pale non-aluminous hornblendes are found among gneisses, crystalline limestones, and other metamorphic rocks. The dark varieties, though also found in similar situations, sometimes even forming entire masses of rock (amphibolite, hornblende-rock, hornblende-schist), are the common forms in granitic and volcanic rocks (syenite, diorite, hornblende-andesite, &c.) The former group naturally gives rise by weathering to various hydrous magnesian silicates, notably to serpentine and talc. In the weathering of the aluminous varieties, silica, lime, magnesia, and a portion of the alkalies are removed, with conversion of part of the earths and the iron into carbonates. The further oxidation of the ferrous carbonate is shown by the yellow and brown crust so commonly to be seen on the surface or penetrating cracks in the hornblende. The change proceeds until a mere internal kernel of unaltered mineral remains, or until the whole has been converted into a ferruginous clay.

Anthophyllite (Rhombic Amphibole $(MgFe)SiO_3$) is a mineral which occurs in bladed, sometimes rather fibrous forms, among the more basic parts of old gneisses; also in zones of alteration round some of the ferro-magnesian minerals of certain gabbros.

Soda-amphiboles resemble ordinary hornblende, but, as their name denotes, they contain a more marked proportion of soda. They include a blue variety called *Glaucophane*, which is found abundantly in certain schists; *Riebeckite*, which is also blue and occurs in some granites and micro-granites; *Arfvedsonite*, a dark greenish or brown variety.

Uralite is the name given to a mineral which was originally pyroxene, but has now by a process of paramorphism acquired the internal cleavage and structure of hornblende (amphibole). Under the microscope a still unchanged kernel of pyroxene may in some specimens be observed in the centre of a crystal surrounded by strongly pleochroic hornblende, with its characteristic cleavage and actinolitic needles (*postea*, p. 617). *Smaragdite* is a beautiful grass-green variety also resulting from the alteration of a pyroxene.

Augite (Monoclinic Pyroxene, CaO 12–27·5, MgO 3–22·5, FeO 1–34, Fe_2O_3 0–10, Al_2O_3 0–11; SiO_2 40–57·4). Divided like hornblende into two groups. 1st. Non-aluminous, with a prevalent green colour (malacolite, coccolite, diopside, sahlite, &c.) 2nd. Aluminous, including generally the dark green or black varieties (common augite, fassaite). It would appear that the substance of hornblende and augite is dimorphous, for the experiments of Berthier, Mitscherlich and G. Rose showed that hornblende, when melted and allowed to cool, assumed the crystalline form of augite; whence it has been inferred that hornblende is the result of slow, and augite of comparatively rapid cooling.[1] Under the microscope, augite in thin slices is only very feebly pleochroic, and presents cleavage lines intersecting at an angle of 87° 5′. It is often remarkable for the amount of extraneous materials enclosed within its crystals. Like some felspars, augite may be found in basalt with merely an outer casing of its own substance, the core being composed of magnetite, of the ground-mass of the surrounding rock, or of some other mineral (Fig. 7). The distribution of augite resembles that of hornblende; the pale, non-aluminous varieties are more specially found among gneisses, marbles, and other crystalline, foliated, or metamorphic rocks; the dark-green or black varieties enter as essential constituents into many igneous rocks of all ages, from Palæozoic up to recent times (diabase, basalt, andesite, &c.) Its weathering also agrees with that of hornblende. The aluminous varieties, containing usually some lime, give rise to calcareous and ferruginous carbonates, from which the fine interstices and cavities of the surrounding rock are eventually filled with threads and kernels of calcite and strings of hydrous ferric oxide. In basalt and dolerite, for example, the weathered surface often acquires a rich yellow colour from the oxidation and hydration of the ferrous oxide.

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[1] On the occurrence of this mineral in schists, see Lossen, *Zeitsch. Deutsch. Geol. Ges.* 1867, pp. 546, 661.

[2] *Wien. Acad.* May 1869. See also Fouqué and Michel-Lévy, *op. cit.* pp. 349, 365.

Omphacite, a granular variety of pyroxene, grass green in colour, and commonly associated with red garnet in the rock known as eclogite.

Diallage, a variety of augite, characterised by its somewhat metallic lustre and foliated aspect, is especially a constituent of gabbro.

Rhombic-Pyroxenes.—There are three rhombic forms of pyroxene, which occur as important constituents of some rocks, Enstatite, Bronzite and Hypersthene. *Enstatite* occurs in lherzolite, serpentine, and other olivine rocks; also in meteorites. *Bronzite* is found under similar conditions to enstatite, from which it is with difficulty separable. It occurs in some basalts and in serpentines; also in meteorites. Bronzite and enstatite weather into dull green serpentinous products. *Bastite* or Schiller-spar is a frequent product of the alteration of Bronzite or Enstatite, and may be observed with its characteristic pearly lustre in serpentine. *Hypersthene* occurs in hypersthenite and hypersthene-andesite; also associated with other magnesian minerals among the crystalline schists.

Olivine (Peridot, MgO 32·4–50·5, FeO 6-29·7, SiO_2 31·6–42·8) forms an essential ingredient of basalt, likewise the main part of various so-called olivine-rocks or peridotites (as lherzolite and pikrite), and occurs in many gabbros; under the microscope with polarized light, gives, when fresh, bright colours, specially red and green, but it is not perceptibly pleochroic. Its orthorhombic outlines can sometimes be readily observed, but it often occurs in irregularly shaped granules or in broken crystals, and is liable to be traversed by fine fissures, which are particularly developed transverse to the vertical axis. It is remarkably prone to alteration. The change begins on the outer surface and extends inwards and specially along the fissures, until the whole is converted either into a green granular or fibrous substance, which is probably in most cases serpentine (Fig. 26), or into a reddish-yellow amorphous mass (limonite).

Hauyne (SiO_2 34·06, Al 27·64, Na_2O 11·79, K_2O 4·96, CaO 10·60, SO_4 11·25) occurs abundantly in Italian lavas, in basalt of the Eifel, and elsewhere.

Nosean (SiO_2 33·79, Al 28·75, Na_2O 26·20, SO_4 11·26), under the microscope, is one of the most readily recognised minerals, showing a hexagonal or quadrangular figure, with a characteristic broad dark border corresponding to the external contour of the crystal, and where weathering has not proceeded too far, enclosing a clear colourless centre. It occurs in minute forms in most phonolites, also in large crystals in some sanidine volcanic rocks. Both hauyne and nosean are volcanic minerals associated with the lavas of more recent geological periods.

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[1] The same results have been obtained recently by Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882, p. 78.

Epidote (Pistacite, CaO 16–30, MgO 0–4·9, Fe_2O_3 7·5–17·24, Al_2O_3 14·47–28·9, SiO_2 33·81–57·65) occurs in many crystalline rocks, as a result of the alteration of other silicates such as felspars and hornblende (see *postea*, p. 618); largely distributed in certain schists and quartzites, sometimes associated with beds of magnetite and hæmatite.

Zoisite is allied to epidote but contains no iron. It occurs in altered basic igneous rocks and also (sometimes in large aggregations) in metamorphic groups.

Vesuvianite (Idocrase, CaO 27·7–37·5, MgO 0–10·6, FeO 0–16, Al_2O_3 10·5–26·1, SiO_2 35–39·7, H_2O 0–2·73) occurs in ejected blocks of altered limestone at Somma, also among crystalline limestones and schists.

Andalusite (Al_2O_3 50·96–62·2, Fe_2O_3 0–5·7, SiO_2 35·3–40·17).—Found in crystalline schists. The variety *Chiastolite*, abundant in some dark clay-slates, is distinguished by the regular manner in which the dark substance of the surrounding matrix has been enclosed, giving a cross-like transverse section. These crystals have been developed in the rock after its formation, and are regarded as proofs of contact-metamorphism. (Book IV. Part VIII.) *Sillimanite* or *Fibrolite* is the name given to a fibrous variety which is not infrequent among schistose rocks.

Dichroite (Cordierite, Iolite, MgO 8·2–20·45, FeO 0–11·58, Al_2O_3 28·72–33·11, SiO_2 48·1–50·4, H_2O 0–2·66) occurs in gneiss, sometimes in large amount (cordierite-gneiss); occasionally as an accessory ingredient in some granites; also in talc-schist. Undergoes numerous alterations, having been found changed into pinite, chlorophyllite, mica, &c.

Scapolites, a series of minerals consisting of silicates of alumina, lime and soda, with a little chlorine. They are found among the cavities of lavas, but more frequently among metamorphic rocks, where they appear in association with altered felspars. *Dipyre*, *Couseranite* and *Meionite* are varieties of the series.

Kyanite (Al_2SiO_5) occurs in bladed aggregates of a beautiful delicate blue colour among schistose rocks; also in granular forms.

Garnet (CaO 0–5·78, MgO 0–10·2, Fe_2O_3 0–6·7, FeO 24·82–39·68, MnO 0–6·43, Al_2O_3 15·2–21·49, SiO_2 35·75–52·11).—The common red and brown varieties occur as essential constituents of eclogite, garnet-rock; and often as abundant accessories in mica-schist, gneiss, granite, &c. Under the microscope, garnet as a constituent of rocks, presents three-sided, four-sided, six-sided, eight-sided (or even rounded) figures according to the angle at which the individual crystals are cut; it is usually clear, but full of flaws or of cavities; passive in polarized light.

Tourmaline (Schorl, CaO 0–2·2, MgO 0–14·89, Na_2O 0–4·95, K_2O 0–3·59, FeO 0–12, Fe_2O_3 0–13·08, Al_2O_3 30·44–44·4, SiO_2 35·2–41·16, B 3·63–11·78, F 1·49–2·58), with quartz, forms tourmaline-rock; associated with some granites; occurs also diffused through many gneisses, schists, crystalline limestones, and dolomites, likewise in sands (see Zircon). Pleochroism strongly marked.

Zircon (ZrO_2 63·5–67·16, Fe_2O_3 0–2, SiO_2 32–35·26) occurs as a chief ingredient in the zircon-syenite of Southern Norway; frequent in granites, diorites, gneisses, crystalline limestones and schists; in eclogite; as clear red grains in some basalts, and also in ejected volcanic blocks; of common occurrence in sands, clays, sandstones, shales and other sedimentary rocks derived from crystalline masses such as granite, etc.

Titanite (Sphene, CaO 21·76–33, TiO_2 33–43·5, SiO_2 30–35), dispersed in small characteristically lozenge-shaped crystals in many syenites, also in granite, gneiss, and in some volcanic rocks (basalt, trachyte, phonolite).

Zeolites.—Under this name is included a characteristic family of minerals, which have resulted from the alteration, and particularly from the hydration, of other minerals, especially of felspars. Secondary products, rather than original constituents of rocks, they often occur in cavities both as prominent amygdales and veins, and in minute interstices only perceptible by the microscope. In these minute forms they very commonly present a finely fibrous divergent structure. As already remarked, a relation may often be traced between the containing rock and its enclosed zeolites. Thus among the basalts of the Inner Hebrides, the dirty green decomposed amygdaloidal sheets are the chief repositories of zeolites, while the firm, compact, columnar beds are comparatively free from these alteration products.[1] Among the more common zeolites are *Analcime*, *Natrolite*, *Prehnite* and *Stilbite*.

Kaolin (Al_2O_3 38·6–40·7, CaO 0–3·5, K_2O 0–1·9, SiO_2 45·5–46·53, H_2O 9–14·54) results from the alteration of potash- and soda-felspars exposed to atmospheric influences. Under the microscope the fine white powdery substance is found to include abundant minute six-sided colourless plates and scales which have been formed by re-crystallization of the decomposed substance of the felspar. The purest white kaolin is called *china-clay*, from its extensive use in the manufacture of porcelain. Ordinary clay is impure from admixture of iron, lime, and other ingredients, among which the débris of the undecomposed constituents of the original rock may form a marked proportion.

Talc (MgO 23·19–35·4, FeO 0–4·5, Al_2O_3 0–5·67, SiO_2 56·62–64·53, H_2O 0–6·65) occurs as an essential constituent of talc-schist, and as an alteration product replacing mica, hornblende, augite, olivine, diallage, and other minerals in crystalline rocks.

Chlorite (MgO 24·9–36, FeO 0–5·9, Fe_2O_3 0–11·36, Al_2O_3 10·5–19·9, SiO_2 30–33·5, H_2O 11·5–16), including several varieties or species, occurs in small green hexagonal tables or scaly vermicular or earthy aggregates; is an essential ingredient of chlorite-schist, and occurs abundantly as an alteration product (of hornblende, &c.) in fine filaments, incrustations, and layers in many crystalline rocks. (See under "Chloritization," *postea*, p. 618.) Among the minerals grouped under the general head of chlorites are *Chlorophæite*, *Clinochlore*, *Delessite*, *Pennine*, *Ripidolite*, and others.

Ottrelite (Chloritoid, H_2O (FeMg) Al_2SiO_7) occurs in small lustrous iron-black or greenish-black lozenge-shaped or six-side plates in certain schists. It resembles chlorite but is at once distinguishable from that mineral by its much greater hardness.

Serpentine (MgO 28–43, FeO 1–10·8, Al_2O_3 0–5·5, SiO_2 37·5–44·5, H_2O 9·5–14·6) is a product of the alteration of pre-existing minerals, and especially of olivine. It occurs in nests, grains, threads, and veins in rocks which once contained olivine[2] (p. 75), also massive as a rock, in which it has replaced olivine, enstatite or some other magnesian bisilicate (pp. 173, 618). Under the microscope it presents, in very thin slices, a pale leek-green or bluish-green base, showing aggregate polarization. Through this base runs a network of dark opaque threads and veinings. Sometimes among these veinings, or through the network of green serpentinous matter in the base, the forms of original olivine crystals may be traced (Figs. 26, 27).

Glauconite (CaO 0–4·9, MgO 0–5·9, K_2O 0–12·9, Na_2O 0–2·5, FeO 3–25·5, Fe_2O_3 0–28·1, Al_2O_3 1·5–13·3, SiO_2 46·5–60·09, H_2O 0–14·7). Found in many stratified formations, particularly among sandstones and limestones, where it envelopes grains of sand, or fills and coats foraminifera and other organisms, giving a general green tint to the rock. It is at present being formed on the sea-floor off the coasts of Georgia and South Carolina, where Pourtales found it filling the chambers of recent polythalamia.

6. CARBONATES. This family of minerals furnishes only four which enter largely into the formation of rocks, viz., Carbonate of Calcium in its two forms, Calcite and Aragonite, Carbonate of Magnesium (and Calcium) in Dolomite, and Carbonate of Iron in Siderite.

Calcite ($CaCO_3$) occurs as (1) an original constituent of many aqueous rocks (limestone, calcareous shale, &c.), either as a result of chemical deposition from water (calc-sinter, stalactites, &c.), or as a secretion by plants or animals[1]; or (2) as a secondary product resulting from weathering, when it is found filling or lining cavities, or diffused through the capillary interstices of minerals and rocks. It probably never occurs as an original ingredient in the massive crystalline rocks, such as granite, felsite, and lavas. Under the microscope, calcite is readily distinguishable by its intersecting cleavage lines, by a frequent twin lamellation (sometimes giving interference colours), strong double refraction, weak or inappreciable pleochroism, and characteristic iridescent polarization tints of grey, rose and blue.

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[1] See Sullivan in Jukes' 'Manual of Geology,' p. 85.

[2] See Tschermak, *Wien. Akad.* lvi. 1867.

From the readiness with which water absorbs carbon-dioxide, from the increased solvent power which it thereby acquires, and from the abundance of calcium in various forms among minerals and rocks, it is natural that calcite should occur abundantly as a pseudomorph replacing other minerals. Thus, it has been observed taking the place of a number of silicates, as orthoclase, oligoclase, garnet, augite and several zeolites; of the sulphates, anhydrite, gypsum, barytes, and celestine; of the carbonates, aragonite, dolomite, cerussite; of the fluoride, fluor-spar; and of the sulphide, galena. Moreover, in many massive crystalline rocks (diorite, dolerite, &c.), which have been long exposed to atmospheric influence, this mineral may be recognised by the brisk effervescence produced by a drop of acid, and in microscopic sections it appears filling the crevices, or sending minute veins among the decayed mineral constituents. Calcite is likewise the great petrifying medium: the vast majority of the animal remains found in the rocky crust of the globe have been replaced by calcite, sometimes with a complete preservation of internal organic structure, sometimes with a total substitution of crystalline material for that structure, the mere outer form of the organism alone surviving.[2]

Aragonite ($CaCO_3$), harder, heavier, and much less abundant than calcite, which is the more stable form of calcium-carbonate; occurs with beds of gypsum, also in mineral veins, in strings running through basalt and other igneous rocks, and in the shells of many mollusca. It is thus always a deposit from water, sometimes from warm mineral springs, sometimes as the result of the internal alteration of rocks, and sometimes through the action of living organisms. Being more easily soluble than calcite, it has no doubt in many cases disappeared from limestones originally formed mainly of aragonite shells, and has been replaced by the more durable calcite, with a consequent destruction of the traces of organic origin. Hence what are now thoroughly crystalline limestones may have been formed by a slow alteration of such shelly deposits (p. 484).

Dolomite (Bitter-spar $(Ca; Mg)CO_3$, p. 151) occurs (1) as an original deposit in massive beds (magnesian limestone), belonging to many different geological formations; (2) as a product of alteration, especially of ordinary limestone or of aragonite (Dolomitization p. 321).

Siderite (Brown Ironstone, Spathic Iron, Chalybite, Ferrous Carbonate, $FeCO_3$) occurs crystallized in association with metallic ores, also in beds and veins of many crystalline rocks, particularly with limestones; the compact argillaceous varieties (clay-ironstone) are found in abundant nodules and beds in the shales of Carboniferous and other formations where they have been deposited from solution in water in presence of decaying organic matter (see pp. 147, 153).

7. SULPHATES. Among the sulphates of the mineral kingdom, only two deserve notice here as important compounds in the constitution of rocks—viz., calcium-sulphate

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[1] Mr. Sorby has investigated the condition in which the calcareous matter of the harder parts of invertebrates exists. He finds that in foraminifera, echinoderms, brachiopods, crustacea, and some lamellibranchs and gasteropods, it occurs as calcite; that in nautilus, sepia, most gasteropods, many lamellibranchs, &c., it is aragonite; and that in not a few cases the two forms occur together, or that the carbonate of lime is hardened by an admixture of phosphate. *Quart. Journ. Geol. Soc.* 1879. Address, p. 61.

[2] See index *sub voc.* Calcite.

or sulphate of lime in its two forms, Anhydrite and Gypsum; and barium-sulphate or sulphate of baryta in Barytes.

Anhydrite ($CaSO_4$) occurs more especially in association with beds of gypsum and rock-salt (see p. 152).

Gypsum (Selenite, $CaSO_4 + 2H_2O$). Abundant as an original aqueous deposit in many sedimentary formations (see p. 152).

Barytes (Heavy Spar, $BaSO_4$). Frequent in veins and especially associated with metallic ores as one of their characteristic vein-stones.

8. PHOSPHATES. The phosphates which occur most conspicuously as constituents or accessory ingredients of rocks are the tricalcic phosphate or Apatite, and triferrous phosphate or Vivianite.

Apatite ($3Ca_3 (PO_4) + CaF_2$) occurs in many igneous rocks (granites, basalts, &c.), in minute hexagonal non-pleochroic needles, giving faint polarization tints; also in large crystals and massive beds associated with metamorphic rocks.

Vivianite (Blue iron-earth, $Fe_3P_2O_8$, $8H_2O$) occurs crystallized in metalliferous veins; the earthy variety is not infrequent in peat-mosses where animal matter has decayed, and is sometimes to be observed coating fossil fishes as a fine layer like the bloom of a plum.

9. FLUORIDES. The element fluorine, though widely diffused in nature, occurs as an important constituent of comparatively few minerals. Its most abundant compound is with Calcium as the common mineral Fluorite. It occurs also with sodium and aluminium in the mineral Cryolite.

Fluorite (Fluor-spar, CaF_2) occurs generally in veins, especially in association with metallic ores.

10. CHLORIDES. There is only one chloride of importance as a constituent of rocks —sodium-chloride or common salt ($NaCl$), which, occurring chiefly in beds, is described among the rocks at p. 148. Carnallite ($KClMgCl_2 6H_2O$), a hydrated chloride of potassium and magnesium, occurs in beds associated with rock-salt, gypsum, &c., in some salt districts (p. 149).

11. SULPHIDES. Sulphur is found united with metals in the form of sulphides, many of which form common minerals. The sulphides of lead, silver, copper, zinc, antimony, &c., are of great commercial importance. Iron-disulphide, however, is the only one which merits consideration here as a rock-forming substance. It is formed at the present day by some thermal springs, and has been developed in many rocks as a result of the action of infiltrating water in presence of decomposing organic matter and iron salts. It occurs in two forms, Pyrite and Marcasite.

Pyrite (Eisenkies, Schwefelkies, FeS_2) occurs disseminated through almost all kinds of rocks, often in great abundance, as among diabases and clay-slates; also frequent in veins or in beds. In microscopic sections of rocks, pyrite appears in small cubical, perfectly opaque crystals, which with reflected light show the characteristic brassy lustre of the mineral, and cannot thus be mistaken for the isometric magnetite, of which the square sections exhibit a characteristic blue-black colour. Pyrite when free from marcasite yields but slowly to weathering. Hence its cubical crystals may be seen projecting still fresh from slates which have been exposed to the atmosphere for several generations.[1]

Marcasite (Hepatic pyrites) occurs abundantly among sedimentary formations, sometimes abundantly diffused in minute particles which impart a blue-grey tint, and speedily weather yellow on exposure and oxidation; sometimes segregated in layers, or replacing the substance of fossil plants or animals; also in veins through crystalline rocks. This form of the sulphide is especially characteristic of stratified fossiliferous rocks, and more particularly of those of Secondary and Tertiary date. It is extremely liable to decomposition. Hence exposure for even a short time to the air causes it to become brown; free sulphuric acid is produced, which attacks the surrounding minerals, sometimes at once forming sulphates, at other times decomposing aluminous silicates and dissolving them in considerable quantity. Dr. Sullivan mentions that the water annually pumped from one mine in Ireland carried up to the surface more than a hundred tons of dissolved silicate of alumina.[1] Iron disulphide is thus an important agent in effecting the internal decomposition of rocks. It also plays a large part as a petrifying medium, replacing the organic matter of plants and animals, and leaving casts of their forms, often with bright metallic lustre. Such casts when exposed to the air decompose.

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[1] For an elaborate paper on the decomposition of Pyrites, see A. A. Julien, *Annals New York Acad. Sci.* vols. iii. and iv.

Pyrrhotine (Magnetic pyrites, Fe_7S_8) is much less abundant than either of the forms of ordinary iron-pyrites, from which it is distinguished by its inferior hardness and its magnetic character.

It will be observed that great differences exist in the relative importance of the minerals above enumerated as constituents of rocks. Professor Rosenbusch points out that they may be naturally arranged in four groups—1st, ores and accessory ingredients (magnetite, hæmatite, ilmenite, apatite, zircon, spinel, titanite), 2nd, magnesian and ferruginous silicates (biotite, amphibole, pyroxene, olivine), 3rd, felspathic constituents (felspar proper, nepheline, leucite, melilite, sodalite, hauyne), 4th, free silica.[2]

§ iii. Determination of Rocks.

Rocks considered as mineral substances are distinguished from each other by certain external characters, such as the size, form, and arrangement of their component particles. These characters, readily perceptible to the naked eye, and in the great majority of cases observable in hand specimens, are termed *megascopic* or *macroscopic* (pp. 81-87), to distinguish them from the more minute features which, being only visible or satisfactorily observable when greatly magnified, are known as *microscopic* (pp. 89-96). The larger (geotectonic) aspects of rock-structure, which can only be properly examined in the field and belong to the general architecture of the earth's crust, are treated of in Book IV.[3]

In the discrimination of rocks, it is not enough to specify their component minerals, for the same minerals may constitute very distinct varieties of rock. For example, quartz and mica form the massive crystalline rock, greisen, the foliated crystalline rock, mica-schist, and the sedimentary rock, micaceous sandstone. Chalk, encrinal limestone, stalagmite, statuary marble are all composed of calcite. It is needful to take note of the megascopic and microscopic structure and texture, the state of aggregation, colour, and other characters of the several masses.

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[1] Jukes' 'Manual of Geology,' p. 65.

[2] *Neues Jahrb.* 1882 (ii.) p. 5.

[3] The student who would pursue physical geology by original research in the field and abroad may consult Boué, 'Guide du Géologue Voyageur,' 2 vols. 1835; Élie de Beaumont, 'Leçons de Géologie pratique,' vol. i. 1845; Penning and Jukes-Brown, 'Field Geology,' 2nd edit. 1880; A. Geikie, 'Outlines of Field Geology,' 4th edit. 1891. F. v. Richthofen. 'Führer für Forschungsreisende,' 1886; Grenville Cole, 'Aids in Practical Geology,' 1891.

Four methods of procedure are available in the investigation and determination of rocks: 1st, megascopic (macroscopic) examination, either by the rough and ready, but often sufficient, appliances for use in the field, or by those for more careful work indoors; 2nd, chemical analysis; 3rd, chemical synthesis; 4th, microscopic investigation.

i. *Megascopic (Macroscopic) Examination.*

Tests in the field.—The instruments indispensable for the investigation of rocks in the field are few in number, and simple in character and application. The observer will be sufficiently accoutred if he carries with him a hammer of such form and weight as will enable him to break off clean, sharp, unweathered chips from the edges of rock-masses, a small lens, a pocket-knife of hard steel for determining the hardness of rocks and minerals, a magnet or a magnetized knife-blade, and a small pocket-phial of dilute hydrochloric acid, or better still some citric acid in powder.

Should the object be to form a collection of rocks, a hammer of at least three or four pounds in weight should be carried: also one or two chisels and a small trimming hammer, weighing about ¼ lb., for reducing the specimens to shape. A convenient size of specimen is 4 × 3 × 1 inches. They should be as nearly as possible uniform in size, so as to be capable of orderly arrangement in the drawers or shelves of a case or cabinet. Attention should be paid not only to obtain a thoroughly fresh fracture of a rock, but also a weathered surface, wherever there is anything characteristic in the weathering. Every specimen should have affixed to it a label, indicating as exactly as possible the locality from which it was taken. This information ought always to be written down in the field at the time of collecting, and should be affixed to or wrapped up with the specimen, before it is consigned to the collecting bag. If, however, the student does not purpose to form a collection, but merely to obtain such chips as will enable him to judge of the characters of rocks, a hammer weighing from 1½ to 2 lbs., with a square face and tapering to a chisel-edge at the opposite end, will be most useful. The advantage of this form is that the hammer can be used not only for breaking hard stones, but also for splitting open shales and other fissile rocks, so that it unites the uses of hammer and chisel.

It is, of course, desirable that the learner should first acquire some knowledge of the nomenclature of rocks, by carefully studying a collection of correctly named and judiciously selected rock-specimens. Such collections may now be purchased at small cost from mineral dealers, or may be studied in the museums of most towns. Having accustomed his eye to the ordinary external characters of rocks, and become familiar with their names, the student may proceed to determine them for himself in the field.

Finding himself face to face with a rock-mass, and after noting its geotectonic characters (Book IV.), the observer will proceed to examine the exposed or weathered surface. The earliest lesson he has to learn, and that of which perhaps he will in after life meet with the most varied illustrations, is the extent to which weathering conceals the true aspect of rocks. From what has been said in previous pages, the nature of some of the alterations will be understood, and further information regarding the chemical processes at work will be found in Book III. The practical study of rocks in the field soon discloses the fact, that while, in some cases, the weathered crust so completely obscures the essential character of a rock that its true nature might not be suspected, in other instances, it is the weathered crust that best reveals the real structure of the mass. Spheroidal crusts of a decomposing yellow ferruginous earthy substance, for example, would hardly be identified as a compact dark basalt, yet, on penetrating within these crusts, a central core of still undecomposed basalt may not unfrequently be discovered. Again, a block of limestone when broken open may present only a uniformly crystalline structure, yet if the weathered surface be examined it may show many projecting fragments of shells, polyzoa, corals, crinoids, or other organisms. The really fossiliferous nature of an apparently unfossiliferous rock may thus be revealed by weathering. Many limestones also might, from their fresh fracture, be set down as tolerably pure carbonate of lime; but from the thick crust of yellow ochre on their weathered faces are seen to be highly ferruginous. Among crystalline rocks, the weathered surface commonly throws light upon the mineral constitution of the mass, for some minerals decompose more rapidly than others, which are thus left isolated and more easily recognisable. In this manner, the existence of quartz in many felspathic rocks may be detected. Its minute blebs or crystals, which to the naked eye or lens are lost among the brilliant facettes of the felspars, stand out amid the dull clay into which these minerals are decomposed.

The depth to which weathering extends should be noted. The student must not be too confident that he has reached its limit, even when he comes to the solid, more or less hard, splintery, and apparently fresh stone. Granite sometimes decomposes into kaolin and sand to a depth of twenty or thirty feet or more. Limestones, on the other hand, have often a mere film of crust, because their substance is almost entirely dissolved and removed by rain (Book III. Part II. Section ii. § 2).

With some practice, the inspection of a weathered surface will frequently suffice to determine the true nature and name of a rock. Should this preliminary examination, and a comparison of weathered and unweathered surfaces, fail to afford the information sought, we proceed to apply some of the simple and useful tests available for field-work. The lens will usually enable us to decide whether the rock is compact and apparently structureless, or crystalline, or fragmental. Having settled this point, we proceed to ascertain the hardness and colour of streak, by scratching a fresh surface of the stone. A drop of acid placed upon the scratched surface or on the powder of the streak may reveal the presence of some carbonate. By practice, considerable facility can be acquired in approximately estimating the specific gravity of rocks merely by the hand. The following table may be of assistance, but it must be understood at the outset that a knowledge of rocks can never be gained from instructions given in books, but must be acquired by actual handling and study of the rocks themselves.

i. A fresh fracture shows the rock to be close-grained, dull, with no distinct structure.[1]

α. H. 0·5 or less up to 1; soft, crumbling or easily scratched with the knife, if not with the finger-nail; emits an earthy smell when breathed upon, does not effervesce with acid; is dark grey, brown, or blue, perhaps red, yellow, or even white = probably some clay rock, such as mudstone, massive shale, or fire-clay (p. 132); or a decomposed felspar-rock, like a close-grained felsite or orthoclase porphyry. If the rock is hard and fissile it may be shale or clay-slate (p. 134).

β. H. 1·5–2. Occurs in beds or veins (perhaps fibrous), white, yellow, or reddish. Sp. gr. 2·2–2·4. Does not effervesce = probably gypsum (pp. 79, 152).

γ. Friable, crumbling, soils the fingers, white, or yellowish, brisk effervescence = chalk, marl, or some pulverulent form of limestone (pp. 139, 149).

δ. H. 3–4. Sp. gr. 2·5–2·7; pale to dark green or reddish, or with blotched and clouded mixtures of these colours. Streak white; feels soapy; no effervescence, splintery to subconchoidal fracture, edges subtranslucent. See serpentine (p. 173).

ε. H. averaging 3. Sp. gr. 2·6–2·8. White, but more frequently bluish-grey, also yellow, brown and black; streak white; gives brisk effervescence = some form of limestone (pp. 139, 149).

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[1] In this table, H. = hardness; Sp. gr. = specific gravity. The scale of hardness usually employed is 1, Talc; 2, Rock-salt or gypsum; 3, Calcite; 4, Fluorite; 5, Apatite; 6, Orthoclase; 7, Quartz; 8, Topaz; 9, Corundum; 10, Diamond.

ζ. H. 3·5–4·5. Sp. gr. 2·8–2·95. Yellowish, white, or pale brown. Powder slowly soluble in acid with feeble effervescence, which becomes brisker when the acid is heated with the powder of the stone. See dolomite (pp. 78, 151).

η. H. 3–4. Sp. gr. 3–3·9. Dark brown to dull black, streak yellow to brown, feebly soluble in acid, which becomes yellow; occurs in nodules or beds, usually with shale; weathers with brown or blood-red crust = brown iron-ore. See clay-ironstone (pp. 147, 153); and limonite (pp. 70, 153); if the rock is reddish and gives a cherry-red streak, see hæmatite (pp. 70, 153).

θ. Sp. gr. 2·55. White, grey, yellowish, or bluish, rings under the hammer, splits into thin plates, does not effervesce, weathered crust white and distinct = perhaps some compact variety of phonolite (p. 166. See also felsite (p. 161), and porphyrite, p. 168).

ι. Sp. gr. 2·9–3·2. Black or dark green, weathered crust yellow or brown = probably some close-grained variety of basalt (p. 170), andesite (p. 167), aphanite (p. 166), or amphibolite (p. 182).

κ. H. 6–6·5, but less according to decomposition. Sp. gr. 2·55–2·7. Can with difficulty be scratched with the knife when fresh. White, bluish-grey, yellow, lilac, brown, red; white streak; sometimes with well defined white weathered crust, no effervescence = probably a felsitic rock (p. 161).

λ. H. 7. Sp. gr. 2·5–2·9. The knife leaves a metallic streak of steel upon the resisting surface. The rock is white, reddish, yellowish, to brown or black, very finely granular or of a horny texture, gives no reaction with acid = probably silica in the form of jasper, hornstone, flint, chalcedony, hälleflinta (pp. 69, 183), adinole (p. 183).

ii. A fresh fracture shows the rock to be glassy.

Leaving out of account some glass-like but crystalline minerals, such as quartz and rock-salt, the number of vitreous rocks is comparatively small. The true nature of the mass in question will probably not be difficult to determine. It must be one of the Massive volcanic rocks (p. 154 *et seq.*) If it occurs in association with siliceous lavas (liparites, trachytes) it will probably be obsidian (p. 162), or pitchstone (p. 163); if it passes into one of the basalt-rocks, as so commonly happens along the edges of dykes and intrusive sheets, it is a glassy form of basalt (p. 171). Each of the three great series of eruptive rocks, Acid, Intermediate, and Basic, has its glassy varieties (see pp. 162, 163, 171).

iii. A fresh fracture shows the rock to be crystalline.

If the component crystals are sufficiently large for determination in the field, they may suggest the name of the rock. Where, however, they are too minute for identification even with a good lens, the observer may require to submit the rock to more precise investigation at home, before its true character can be ascertained. For the purposes of field-work, however, the following points should be noted.

α. The rock can be easily scratched with the knife.

(*a*) Effervesces briskly with acid = limestone.

(*b*) Powder of streak effervesces in hot acid. See dolomite (p. 151).

(*c*) No effervescence with acid: may be granular crystalline gypsum (alabaster) or anhydrite (pp. 79, 152).

β. The rock is not easily scratched. It is almost certainly a silicate. Its character should be sought among the massive crystalline rocks (p. 154). If it be heavy, appear to be composed of only one mineral, and have a marked greenish tint, it may be some kind of amphibolite (p. 182); if it consist of some white mineral (felspar) and a green mineral which gives it a distinct green colour, while the weathered crust shows more or less distinct effervescence, it may be a fine-grained diorite (p. 165), or diabase (p. 170); if it be grey and granular, with striated felspars and dark crystals (augite and magnetite), with a yellowish or brownish weathered crust, it is probably a dolerite (p. 169) or andesite (p. 167); if it be compact, finely-crystalline, scratched with difficulty, showing crystals of orthoclase, and with a bleached argillaceous weathered crust, it is probably an orthoclase-porphyry (p. 164), or quartz-porphyry (p. 160). The occurrence of distinct blebs or crystals of quartz in the fresh fracture or weathered face will suggest a place for the rock in the quartziferous crystalline series (granites, quartz-porphyries, rhyolites), or among the gneisses and schists.

iv. A fresh fracture shows the rock to have a foliated structure.

The foliated rocks are for the most part easily recognisable by the prominence of their component minerals (p. 175). Where the minerals are so intimately mingled as not to be separable by the use of the lens, the following hints may be of service:—

α. The rock has an unctuous feel, and is easily scratched. It may be talc-schist (p. 183), chlorite-schist (p. 183), sericitic mica-schist (p. 185), or foliated serpentine (p. 183).

β. The rock emits an earthy smell when breathed on, is harder than those included in *α*, is fine-grained, dark-grey in colour, splits with a slaty fracture and contains perhaps scattered crystals of iron-pyrites or some other mineral. It is some argillaceous-schist or clay-slate, the varieties of which are named from the predominant enclosed mineral, as chiastolite-slate, andalusite-schist, ottrelite-schist, &c. (p. 179); if it has a silky lustre it may be phyllite.

γ. The rock is composed of a mass of ray-like or fibrous crystals matted together. If the fibres are exceedingly fine, silky, and easily separable, it is probably asbestos; if they are coarser, greenish to white, glassy, and hard, it is probably an actinolite-schist (p. 182). Many serpentines are seamed with veins of the fine silky fibrous variety termed chrysotile, which is easily scratched.

δ. The rock has a hardness of nearly 7, and splits with some difficulty along micaceous folia. It is probably a quartzose variety of mica-schist, quartz-schist, or gneiss (pp. 179, 184, 185).

ε. The rock shows on its weathered surface small particles of quartz and folia of mica in a fine decomposing base. It is probably a fine-grained variety of mica-schist or gneiss.

v. A fresh fracture shows the rock to have a fragmental (clastic) structure.

Where the component fragments are large enough to be seen by the naked eye or with a lens, there is usually little difficulty in determining the true nature and proper name of the rock. Two characters require to be specially considered—the component fragments and the cementing paste.

1. *The Fragments.*—According to the shape, size, and composition of the fragments, different names are assigned to clastic rocks.

α. Shape.—If the fragments are chiefly rounded, the rock may be sought in the sand and gravel series (p. 127), while if they are large and angular, it may be classed as a breccia (p. 130). Some mineral substances, however, do not acquire rounded outlines, even after long-continued attrition. Mica, for example, splits up into thin laminæ, which may be broken into small flakes or spangles, but never become rounded granules. Other minerals, also, which have a ready cleavage, are apt to break up along their cleavage-planes, and thus to retain angular contours. Calc-spar is a familiar example of this tendency. Organic remains composed of this mineral (such as crinoids and echinoids) may often be noticed in a very fragmentary condition, having evidently been subjected to long-continued comminution. Yet angular outlines and fresh or little worn cleavage-surfaces may be found among them. Many limestones consist largely of sub-angular organic débris. Angular inorganic detritus is characteristic of volcanic breccias and tuffs (p. 135).

β. Size.—Where the fragments are hard, rounded, or sub-angular quartzose grains, the size of a pin's head or less, the rock is probably some form of sandstone (p. 131). Where they range up to the size of a pea, it may be a pebbly sandstone, fine conglomerate or grit; where they vary from the size of a pea to that of a walnut, it is an ordinary gravel or conglomerate; where they range up to the size of a man's head or larger, it is a coarse shingle or conglomerate. A considerable admixture of sub-angular stones makes it a brecciated conglomerate or breccia; but where the materials are loosely aggregated, the deposit may be some kind of glacial drift, such as moraine-stuff or boulder-clay (p. 133). Large angular and irregular blocks are characteristic of coarse volcanic agglomerates (p. 137).

γ. Composition.—In the majority of cases, the fragments are of quartz, or at least of some siliceous and enduring mineral. Sandstones consist chiefly of rounded quartz-grains (p. 131). Where these are unmixed with other ingredients, the rock is sometimes distinguished as a quartzose sandstone. Such a rock when indurated becomes quartzite (p. 180). Among the quartz-grains, minute fragments of other minerals may be observed. When any one of these is prominent, it may give a name to the variety of sandstone, as felspathic, micaceous (p. 104). Volcanic tuffs and breccias are characterised by the occurrence of lapilli (very commonly *cellular*) of the lavas from the explosion of which they have been formed. Among interbedded volcanic rocks, the student will meet with some which he may be at a loss whether to class as volcanic, or as formed of ordinary sediment. They consist of an intermixture of volcanic detritus with sand or mud, and pass on the one side into true tuffs, on the other into sandstones, shales, limestones, etc. If the component fragments of a non-crystalline rock give a brisk effervescence with acid, they are calcareous, and the rock (most likely a limestone, or at least of calcareous composition) may be searched for traces of fossils.

2. *The Paste.*—It sometimes happens that the component fragments of a clastic rock cohere merely from pressure and without any discoverable matrix. This is occasionally the case with sandstone. Most commonly, however, there is some cementing paste. If a drop of weak acid produces effervescence from between the component non-calcareous grains of a rock, the paste is calcareous. If the grains are coated with a red crust which, on being bruised between white paper, gives a cherry-red powder, the cementing material is the anhydrous peroxide of iron. If the paste is yellow or brown it is probably in great part the hydrous peroxide of iron. A dark brown or black matrix which can be dissipated by heating is bituminous. Where the component grains are so firmly cemented in an exceedingly hard matrix that they break across rather than separate from each other when the stone is fractured, the paste is probably siliceous.

Determination of Specific Gravity.—The student will find this character of considerable advantage in enabling him to discriminate between rocks. He may acquire some dexterity in estimating, even with the hand, the probable specific gravity of substances; but he should begin by determining it with a balance. Jolly's spring balance is a simple and serviceable instrument for this purpose. It consists of an upright stem having a graduated strip of mirror let into it, in front of which hangs a long spiral wire, with rests at the bottom for weighing a substance in air and in water. For most purposes it is sufficiently accurate, and a determination can be made with it in the course of a few minutes.[1] Another and more convenient instrument has been invented by W. N. Walker, consisting of a lever graduated into inches and tenths, and resting on a knife-edge stand, on one side of which is placed a movable weight, while on the long graduated side the substance to be weighed is suspended. This instrument has the advantage of not being so liable to get out of order as other contrivances.[2]

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[1] Jolly's spring balance can be obtained through any optician or mineral dealer from Berberich, of Munich, for nine florins or 27*s*. In the United States it is manufactured by Geo. Wade & Co., at the Hoboken Institute.

[2] See *Geol. Mag.* 1883, p. 109, for a description and drawing of this instrument, and the manner of using it. It may be obtained of Lowden, optician, Dundee, and How & Co., Farringdon Street, London. Its price is 31*s*. 6*d*.

Mechanical Analysis.—Much may be learnt regarding the composition of a rock by reducing it to powder. In the case of many sandstones and clays this reduction may easily be effected by drying the stone and crumbling it between the fingers. But where the material is too compact for such treatment some fragments of it placed within folds of paper upon a surface of steel may be reduced to powder by a few smart blows of a hammer. The powder can be sifted through sieves of varying degrees of fineness and the separate fragments may be picked out with a fine brush and examined with a lens. If they are dark in colour they may be placed on white paper, if light-coloured they are more readily observed upon a black paper. Portions of this powder may be carefully washed and mounted with Canada balsam on glass, as in the way described below for microscopic slices. In this way the constituent minerals of many crystalline rocks may be isolated and studied with great facility. For purposes of comparison specimens of the rock-forming minerals should be procured and treated in a similar way. A series of typical preparations of the powder or minute fragments of such minerals affords to the student an admirable basis from which to start in his study of the crystallographic and optical characters of the minerals which he will require to identify among the constituents of rocks.

Another method of isolating the several components of certain rocks is by washing the triturated materials in water and allowing the sediment to subside. The finer and lighter particles may be drawn off, while the coarser and heavier grains will sink according to their respective specific gravities, and may then be separated and collected. This may be done by means of a wide tube with a stop-cock at the bottom, or by gently washing the powder with water on an inclined surface, when, as in the analogous treatment of veinstones and ores in mining, the particles arrange themselves according to their respective gravities, the lightest being swept away by the current.

Magnetic particles may be extracted with a magnet, the end of which is preserved from contact with the powder by being covered with fine tissue-paper. An electro-magnet will at once withdraw the particles of minerals which contain far too little iron to be ordinarily recognised as magnetic; in this way the particles of a ferruginous magnesian mica may in a few seconds be gathered out of the powder of a granite.[1]

Where the difference between the specific gravity of the component minerals of a rock is slight, they may be separated by means of a solution of given density. Mr. E. Sonstadt proposed the use of a saturated solution of iodide of mercury in iodide of potassium, which has a maximum density of nearly 3·2.[2] Rohrbach's solution, consisting of iodide of mercury and iodide of barium, has a density of as much as 3·588.[3] More serviceable is the solution of borotungstate of cadmium, with a density of 3·28, proposed by D. Klein.[4] The powder of a rock being introduced into one of these liquids, those particles whose specific gravity exceeds that of the liquid will sink to the bottom, while those which are lighter will float. This process allows of the separation of the felspars from each other, and at once eliminates the heavy minerals such as hornblende, augite, and black mica. By the addition of water or other liquid, as the case may be, the specific gravity may be reduced, and different solutions of given density may be employed for determining and isolating rock-constituents. This method of analysis is important in affording a ready means of separating the quartz and felspar of a rock.[5]

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[1] *Mém. Acad. des Sci.* xxxii. No. 11; Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 115.

[2] *Chem. News*, xxix. (1874), p. 128.

[3] *Neues Jahrb.* 1883, p. 186.

[4] *Compt. rend.* xciii. (1881), p. 318. More recently R. Brauns has introduced methylene iodide, which gives a density of 3·33 and is diluted with benzole. *Neues Jahrb.* 1886, ii. p. 72. See also J. W. Retgers, *op. cit.* 1889, ii. p. 185.

[5] Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' p. 117. Thoulet, *Bull. Soc. Min. France*, ii. (1879), p. 17. A cheap form of instrument for isolating minerals by means of heavy solutions is described by Mr. J. W. Evans, *Geol. Mag.* 1891, p. 67.

Hydrofluoric acid may be used in separating the mineral constituents of rocks. The rock to be studied is reduced to powder and introduced gently into a platinum capsule containing the concentrated acid. During the consequent effervescence, the mixture is cautiously stirred with a platinum spatula. Some minerals are converted into fluorides, others into fluosilicates, while some, particularly the iron-magnesia species, remain undissolved. The thick jelly of silica and alumina is removed with water, and the crystalline minerals lying at the bottom can then be dried and examined. By arresting the solution at different stages the different minerals may be isolated. This process is admirably adapted for collecting the pyroxene of pyroxenic rocks.[1]

ii. *Chemical Analysis.*

The determination of the chemical composition of rocks by detailed analysis in the wet way, demands an acquaintance with practical chemistry which comparatively few geologists possess, and is consequently for the most part left in the hands of chemists, who are not geologists. But as some theoretical questions in geology involve a considerable knowledge of chemical processes, so a satisfactory analysis of rocks is best performed by one who understands the nature of the geological problems on which such an analysis may be expected to throw light. As a rule, detailed chemical analysis lies out of the sphere of a geologist's work : yet the wider his knowledge of chemical laws and methods the better. He should at least be able to employ with accuracy the simpler processes of chemical research.

Treatment with Acid.—The geologist's accoutrements for the field should include a small bottle of powered citric acid, or one with a mineral acid, and provided with a glass stopper prolonged downwards into a point. Dilute hydrochloric acid has been commonly employed ; but H. C. Bolton proposed in 1877 the use of organic acids in place of the usual mineral acids. Citric acid is particularly serviceable for the purpose, and has the advantage over the mineral acids that it can be carried in powder, and a strong solution of it in water can be made in such quantity and at such time as may be required. A little of the powder placed with the point of a knife on a surface of limestone and moistened with a drop of water will give the proper reaction.[2]

When a drop of acid gives effervescence upon a surface of rock, the reaction is caused by the liberation of bubbles of carbon dioxide, as this oxide is replaced by the more powerful acid. Hence effervescence is an indication of the presence of carbonates, and when brisk is specially characteristic of calcium-carbonate. Limestone and markedly calcareous rocks may thus at once be detected. By the same means, the decomposition of such rocks as dolerite may be traced to a considerable distance inward from the surface, the original lime-bearing silicate of the rock having been decomposed by infiltrating rain-water, and partially converted into carbonate of lime. This carbonate being far more sensitive to the acid-test than the other carbonates usually to be met with among rocks, a drop of weak cold acid suffices to produce abundant effervescence even from a crystalline face. But the effervescence becomes much more marked if we apply the acid to the powder of the stone. For this purpose, a scratch may be made and then touched with acid, when a more or less copious discharge of carbonic acid may be obtained, where otherwise it might appear so feebly as perhaps even to escape observation. Some carbonates, dolomite for example, are hardly affected by acid until it is heated. This is done by placing some fragments of the substance at the bottom of a test-tube, covering them with acid and applying a flame.

It is a convenient method of roughly estimating the purity of a limestone, to place a fragment of the rock in acid. If there is much impurity (clay, sand, oxide of iron, &c.), this will remain behind as an insoluble residue, and may then be further tested chemically, or examined with the microscope. In this way many limestones among the crystalline schists may be dissolved in acetic acid, leaving a residue of pyroxenes, amphiboles, micas or other silicates. Of course the acid, especially if strong mineral acid is employed, may attack some of the non-calcareous constituents, so that it cannot be concluded that the residue absolutely represents everything present in the rock except the carbonate of lime; but the proportion of non-calcareous matter so dissolved by the acid will usually be small.

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[1] Fouqué and Michel-Lévy, *op. cit.* p. 116.

[2] *Ann. New York Acad. Sci.* i. (1879) p. 1. *Chem. News*, xxxvi.. xxxvii., xxxviii., xliii.

Further chemical processes.—A thorough chemical analysis of a rock or mineral is indispensable for the elucidation of its composition. But there are several processes by which, until that complete analysis has been made, the geologist may add to his knowledge of the chemical nature of the objects of his study. It is commonly the case that minerals about which he may be doubtful are precisely those which, from their small size, are most difficult of separation from the rest of the rock preparatory to analytical processes. The mineral apatite, for example, occurs in minute hexagonal prisms, which on cross-fracture might be mistaken for nepheline, or even sometimes for quartz. If, however, a drop of nitric acid solution of molybdate of ammonia be placed upon one of these crystals, a yellow precipitate will appear if it be apatite. Nepheline, which is another hexagonal mineral likewise abundant in some rocks, gives no yellow precipitate with the ammonia solution, while if a drop of hydrochloric acid be put over it, crystals of chloride of sodium or common salt will be obtained. These reactions can be observed even with minute crystals or fragments, by placing them on a glass slide under the microscope and using an exceedingly attenuated pipette for dropping the liquid on the slide.[1]

Two ingenious applications of chemical processes to the determination of minute fragments of minerals are now in use. In one of these, devised by Boricky,[2] hydrofluosilicic acid of extreme purity is employed. This acid decomposes most silicates, and forms from their bases hydrofluosilicates. A particle about the size of a pin's head of the mineral to be examined is fixed by its base upon a thin layer of Canada balsam spread upon a slip of glass, and a drop of the acid is placed upon it. The preparation is then set in moist air near a saucer of water under a bell-glass for twenty-four hours, after which it is enclosed in dry air, with chloride of calcium. In a few hours the hydrofluosilicates crystallize out upon the balsam and can be examined with the microscope. Those of potassium take the form of cubes, of sodium hexagonal prisms, &c.

The second process, devised by Szabo, consists in utilizing the colorations given to the flame of a Bunsen-burner by sodium and potassium. An elongated splinter of the mineral to be examined is first placed in the outer or oxidizing part of the flame near the base, and then in the reducing part further up and nearer the centre. The amount of sodium present in the mineral is indicated by the extent to which the flame is coloured yellow. The potassium is similarly estimated, but the flame is then looked at with cobalt glass, so as to eliminate the influence of the sodium.[3]

Blow-pipe Tests.—The chemical tests with the blow-pipe are simple, easily applied, and require only patience and practice to give great assistance in the determination of minerals. If unacquainted with blow-pipe analysis, the student must refer to one or other of the numerous text-books on the subject, some of which are mentioned below.[1] For early practice the following apparatus will be found sufficient:—

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[1] An excellent treatise on the chemical examination of minerals under the microscope is that by MM. Klement and Renard, 'Réactions microchemiques à cristaux et leur application en analyse qualitative,' Brussels, 1886. See also H. Behrens, *Ann. École Polytechnique de Delft*, i. 1885 p. 176; *Neues Jahrb.* vii. Beilage Band. p. 435; *Zeitsch. f. Analyt. Chemie*, xxx. ii. p. 126-174 (1891).

[2] *Archiv Naturwiss. Landesdurchforschung von Böhmen*, iii. fasc. 3, 1876. 'Elemente einer neuen chemisch-mikroskopischen Mineral- und Gesteinsanalyse.' Prag, 1877.

[3] Szabo, 'Ueber eine neue Methode die Felspathe auch in Gesteinen zu bestimmen.' Buda-Pest, 1876.

1. Blow-pipe.
2. Thick-wicked candle, or a tin box filled with the material of Child's night-lights, and furnished with a piece of Freyberg wick in a metallic support.
3. Platinum-tipped forceps.
4. A few pieces of platinum wire in lengths of three or four inches.
5. A few pieces of platinum foil.
6. Some pieces of charcoal.
7. A number of closed and open tubes of hard glass.
8. Three small stoppered bottles containing sodium-carbonate, borax, and microcosmic salt.
9. Magnet.

This list can be increased as experience is gained. The whole apparatus may easily be packed into a box which will go into the corner of a portmanteau.

iii. *Chemical Synthesis.*

As already remarked (p. 64), much interesting light has been thrown on the natural conditions in which minerals and rocks have been formed, by actual experiments in which these bodies are reproduced artificially. Since the classic experiments of Hall much progress has been made in this subject, notably from the prolonged and admirable researches carried on in Paris by Professor Daubrée and by Messrs. Fouqué and Michel-Lévy. To some of the results obtained by these observers reference will be made in Book III. Part I. Sect. iv. The processes of investigation have been grouped in three classes. 1st. Those by the 'dry way' as in fusion and sublimation, sometimes simply, sometimes with the intervention of a mineralizing agent such as borax, borates, fluorides, chlorides, &c. 2nd. Those by the 'wet way' where water or steam are used as dissolvants either by themselves or with the aid of some mineralizing agent, and 3rd, Those where some combination of the two foregoing methods is employed, that is, where water or steam is made to act at a high temperature and under great pressure.[2]

iv. *Microscopic Investigation.*[3]

The value of the microscope as an aid in geological research is now everywhere acknowledged. Some information may here be given as to the methods of procedure in microscopical inquiry.

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[1] The great work on the blow-pipe is Plattner's, of which an English translation has been published. Elderhorst's 'Manual of Qualitative Blow-pipe Analysis and Determinative Mineralogy,' by H. B. Nason and C. F. Chandler (Philadelphia: N. S. Porter and Coates), is a smaller but useful volume; while still less pretending is Scheerer's 'Introduction to the Use of the Mouth Blow-pipe,' of which a third edition by H. F. Blandford was published in 1875 by F. Norgate. An admirable work of reference will be found in Professor Brush's 'Manual of Determinative Mineralogy' (New York: J. Wiley and Son). F. v. Kobell's 'Tafeln zur Bestimmung der Mineralien' (Munich) are useful. A valuable summary will be found in Prof. Cole's 'Aids in Practical Geology,' 1891.

[2] See on this subject Daubrée's great work 'Géologie Expérimentale,' 1879; Fouqué et Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882; Stanislas Meunier, 'Les Méthodes de Synthèse en Minéralogie,' 1891; also *postea*, p. 302 *et seq.*

[3] On the microscopic investigation of rocks consult Fouqué and Michel-Lévy, 'Minéralogie Micrographique,' 2 vols. Paris, 1879; Michel-Lévy, 'Les Minéraux des Roches,' Paris, 1888; Michel-Lévy and Lacroix, 'Tableaux des Minéraux des Roches,' 1889; Rosenbusch, 'Mikroskopische Physiographie der Mineralien und Gesteine,' 2 vols., one of which has been translated into English by Iddings and published by Macmillan and Co.; also his 'Hülfstabellen

1. Preparation of microscopic slides of rocks and minerals. — The observer ought to be able to prepare his own slices, and in many cases will find it of advantage to do so, or at least personally to superintend their preparation by others. It is desirable that he should know at the outset that no costly or unwieldy set of apparatus is needful for his purpose. If he is resident in one place and can accommodate a cutting machine, such as a lapidary's lath, he will find the process of preparing rock-slices greatly facilitated.[1] The thickness of each slice must be mainly regulated by the nature of the rock, the rule being to make the slice as thin as can conveniently be cut, so as to save labour in grinding down afterwards. Perhaps the thickness of a shilling may be taken as a fair average. The operator, however, may still further reduce this thickness by cutting and polishing a face of the specimen, cementing that on glass in the way to be immediately described, and then cutting as close as possible to the cemented surface. The thin slice thus left on the glass can then be ground down with comparative ease.

Excellent rock-sections, however, may be prepared without any machine, provided the operator possesses ordinary neatness of hand and patience. He must procure as thin chips as possible. Should the rocks be accessible to him in the field, he should select the freshest portions of them, and by a dexterous use of the hammer, break off from a sharp edge a number of thin splinters or chips, out of which he can choose one or more for rock-slices. These chips may be about an inch square. It is well to take several of them, as the first specimen may chance to be spoiled in the preparation. The geologist ought also always to carry off a piece of the same block from which his chip is taken, that he may have a specimen of the rock for future reference and comparison. Every such hand-specimen, as well as the chips belonging to it, ought to be wrapped up in paper on the spot where it is obtained, and with it should be placed a label containing the name of the locality and any notes that may be thought necessary. It can hardly be too frequently reiterated that all such field-notes ought as far as possible to be written down on the ground, when the actual facts are before the eye for examination.

Having obtained his thin slices, either by having them slit with a machine or by detaching with a hammer as thin splinters as possible, the operator may proceed to the preparation of them for the microscope. For this purpose the following simple apparatus is all that is absolutely needful, though if a grinding-machine be added it will save time and labour.

List of Apparatus required in the Preparation of Thin Slices of Rocks and Minerals for Microscopical Examination.

1. A cast-iron plate ¼ inch thick and 9 inches square.
2. Two pieces of plate-glass, 9 inches square.

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zur Mikroskopischen Mineralbestimmung,' 1888, translated into English by F. H. Hatch and published by Swan Sonnenschein & Co.; F. Rutley, 'Rock-forming Minerals,' London, 1888, and Prof. Cole's volume above cited.

[1] A machine well adapted for both cutting and polishing was devised some years ago by Mr. J. B. Jordan, and may be had of Messrs. Cotton and Johnson, Gerrard Street, Soho, London, for £10, 10*s*. Another slicing and polishing machine, invented by Mr. F. G. Cuttell, costs £6, 10*s*. These machines are too unwieldy to be carried about the country by a field-geologist. Fuess of Berlin supplies two small and convenient hand-instruments, one for slicing, the other for grinding and polishing. The slicing-machine is not quite so satisfactory for hard rocks as one of the larger, more solid forms of apparatus worked by a treadle. But the grinding-machine is useful, and might be added to a geologist's outfit without material inconvenience. If a lapidary is within reach, much of the more irksome part of the work may be saved by getting him to cut off the thin slices in directions marked for him upon the specimens. Many lapidaries now undertake the whole labour of cutting and mounting microscopic slides.

3. A Water of Ayr stone, 6 inches long by 2½ inches broad.
4. Coarse emery (1 lb. or so at a time).
5. Fine or flour-emery (ditto).
6. Putty powder (1 oz.)
7. Canada balsam. (There is an excellent kind prepared by Rimmington, Bradford, specially for microscopic preparations, and sold in shilling bottles.)
8. A small forceps, and a common sewing-needle with its head fixed in a cork.
9. Some oblong pieces of common flat window-glass ; 2 × 1 inches is a convenient size.
10. Glasses with ground edges for mounting the slices upon. They may be had at any chemical instrument maker's in different sizes, the commonest in this country being 3 × 1 inches, though this size is rather too long for convenient handling on a rotating stage.
11. Thin covering-glasses, square or round. These are sold by the ounce ; ¼ oz. will be sufficient to begin with.
12. A small bottle of spirits of wine.

The first part of the process consists in rubbing down and polishing one side of the chip or slice, if this has not already been done in cutting off a slice affixed to glass, as above mentioned. We place the chip upon the wheel of the grinding-machine, or, failing that, upon the iron plate, with a little coarse emery and water. If the chip is so shaped that it can be conveniently pressed by the finger against the plate and kept there in regular horizontal movement, we may proceed at once to rub it down. If, however, we find a difficulty, from its small size or otherwise, in holding the chip, one side of it may be fastened to the end of a bobbin or other convenient bit of wood by means of a cement formed of three-parts of resin and one of beeswax, which is easily softened by heating. A little practice will show that a slow, equable motion with a certain steady pressure is most effectual in producing the desired flatness of surface. When all the roughnesses have been removed, which can be told after the chip has been dipped in water so as to remove the mud and emery, we place the specimen upon the square of plate-glass, and with flour-emery and water continue to rub it down until all the scratches caused by the coarse emery have been removed and a smooth polished surface has been produced.[1] Care should be taken to wash the chip entirely free of any grains of coarse emery before the polishing on glass is begun. It is desirable also to reserve the glass for polishing only. The emery gets finer and finer the longer it is used, so that by remaining on the plate it may be used many times in succession. Of course the glass itself is worn down, but by using alternately every portion of its surface and on both sides, one plate may be made to last a considerable time. If after drying and examining it carefully, we find the surface of the chip to be polished and free from scratches, we may advance to the next part of the process. But it will often happen that the surface is still finely scratched. In this case we may place the chip upon the Water of Ayr stone and with a little water gently rub it to and fro. It should be held quite flat. The Water of Ayr stone, too, should not be allowed to get worn into a hollow, but should also be kept quite flat, otherwise we shall lose part of the chip. Some soft rocks, however, will not take an unscratched surface even with the Water of Ayr stone. These may be finished with putty powder, applied with a bit of woollen rag.

The desired flatness and polish having been secured, and all trace of scratches and dirt having been completely removed, we proceed to a further stage, which consists in grinding down the opposite side and reducing the chip to the requisite degree of thinness. The first step is now to cement the polished surface of the chip to one of the pieces of common glass. A thin piece of iron (a common shovel does quite well) is heated over a fire, or is placed between two supports over a gas-flame.[1] On this plate must be laid the piece of glass to which the slice is to be affixed, together with the slice itself. A little Canada balsam is dropped on the centre of the glass and allowed to remain until it has acquired the necessary consistency. To test this condition, the point of a knife should be inserted into the balsam, and on being removed should be rapidly cooled by being pressed against some cold surface. If it soon becomes hard enough to resist the pressure of the finger nail, it has been sufficiently heated. Care, however, must be observed not to let it remain too long on the hot plate ; for it will then become brittle and start from the glass at some future stage, or at least will break away from the edges of the chip and leave them exposed to the risk of being frayed off. The heat should be kept as moderate as possible, for if it becomes too great it may injure some portions of the rock. Chlorite, for example, is rendered quite opaque if the heat is so great as to drive off its water.

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[1] Exceedingly impalpable emery powder may be obtained by stirring some of the finest emery in water, and after the coarse particles have subsided, pouring off the liquid and allowing the fine suspended dust gradually to subside. Filtered and dried, the residue can be kept for the more delicate parts of the polishing.

When the balsam is found to be ready, the chip, which has been warmed on the same plate, is lifted with the forceps, and laid gently down upon the balsam. It is well to let one end touch the balsam first, and then gradually to lower the other, as in this way the air is driven out. With the point of a needle or a knife the chip should be moved about a little, so as to expel any bubbles of air and promote a firm cohesion between the glass and the stone. The glass is now removed with the forceps from the plate and put upon the table, and a lead weight or other small heavy object is placed upon the chip, so as to keep it pressed down until the balsam has cooled and hardened. If the operation has been successful, the slide ought to be ready for further treatment as soon as the balsam has become cold. If, however, the balsam is still soft, the glass must be again placed on the plate and gently heated, until on cooling, the balsam fulfils the condition of resisting the pressure of the finger-nail.

Having now produced a firm union of the chip and the glass, we proceed to rub down the remaining side of the stone with coarse emery on the iron plate as before. If the glass cannot be held in the hand or moved by the simple pressure of the fingers, which usually suffices, it may be fastened to the end of the bobbin with the cement as before. When the chip has been reduced until it is tolerably thin ; until, for example, light appears through it when held between the eye and the window, we may, as before, wash it clear of the coarse emery and continue the reduction of it on the glass plate with fine emery. Crystalline rocks, such as granite, gneiss, diorite, dolerite, and modern lavas, can be thus reduced to the required thinness on the glass plate. Softer rocks may require gentle treatment with the Water of Ayr stone.

The last parts of the process are the most delicate of all. We desire to make the section as thin as possible, and for that purpose continue rubbing until after one final attempt we may perhaps find to our dismay that great part of the slice has disappeared. The utmost caution should be used. The slide should be kept as flat as possible, and looked at frequently, that the first indications of disruption may be detected. The thinness desirable or attainable depends in great measure upon the nature of the rock. Transparent minerals need not be so much reduced as more opaque ones. Some minerals, indeed, remain absolutely opaque to the last, like pyrite, magnetite, and ilmenite.

The slide is now ready for the microscope. It ought always to be examined with that instrument at this stage. We can thus see whether it is thin enough, and if any chemical tests are required they can readily be applied to the exposed surface of the slice. If the rock has proved to be very brittle, and we have only succeeded in procuring a thin slice after much labour and several failures, nothing further should be done with the preparation, unless to cover it with glass, as will be immediately explained, which not only protects it, but adds to its transparency. But where the slice is not so fragile, and will bear removal from its original rough scratched piece of glass, it should be transferred to one of the glass-slides (No. 10). For this purpose, the preparation is once more placed on the warm iron plate, and close alongside of it is put one of the pieces of glass which has been carefully cleaned, and on the middle of which a little Canada balsam has been dropped. The heat gradually loosens the cohesion of the slice, which is then very gently pushed with the needle or knife along to the contiguous clean slip of glass. Considerable practice is needed in this part of the work, as the slice, being so thin, is apt to go to pieces in being transferred. A gentle inclination of the warm plate, so that a tendency may be given to the slice to slip downwards of itself on to the clean glass, may be advantageously given. We must never attempt to lift the slice. All shifting of its position should be performed with the point of the needle or other sharp instrument. If it goes to pieces we may yet be able to pilot the fragments to their resting-place on the balsam of the new glass, and the resulting slide may be sufficient for the required purpose.

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[1] A piece of wire-gauze placed over the flame, with an interval of an inch or more between it and the overlying thin iron plate, tends to diffuse the heat and prevent the balsam from being unequally heated.

When the slice has been safely conducted to the centre of the glass slip, we put a little Canada balsam over it, and warm it as before. Then taking one of the thin cover-glasses with the forceps, we allow it gradually to rest upon the slice by letting down first one side, and then by degrees the whole. A few gentle circular movements of the cover-glass with the point of the needle or forceps may be needed to ensure the total disappearance of air-bubbles. When these do not appear, and when, as before, we find that the balsam has acquired the proper degree of consistence, the slide containing the slice is removed, and placed on the table with a small lead weight above it in the same way as already described. On becoming quite cold and hard the superabundant balsam round the edge of the cover-glass may be scraped off with a knife, and any which still adheres to the glass may be removed with a little spirits of wine. Small labels should be kept ready for affixing to the slides to mark localities and reference numbers. Thus labelled, the slide may be put away for future study and comparison.

The whole process seems perhaps a little tedious. But in reality much of it is so mechanical, that after the mode of manipulation has been learnt by a little experience, the rubbing-down may be done while the operator is reading. Thus in the evening, when enjoying a pleasant book after his day in the field, he may at the same time, after some practice, rub down his rock-chips, and thus get over the drudgery of the operation almost unconsciously.

Boxes, with grooved sides or with flat trays for carrying microscopic slides, are sold in different sizes. Such boxes are most convenient for a travelling equipage, as they go into small space, and with the help of a little cotton-wool they hold the glass slides firmly without risk of breakage. For a final resting-place, a case with shallow trays or drawers in which the slides can lie flat is most convenient.

2. **The Microscope.**—Unless the observer proposes to enter into great detail in the investigation of the minuter parts of rock-structure, he does not require a large and expensive instrument. For most geological purposes, objectives of 2, 1, and ¼ inch focal length are sufficient. But it is desirable also for special work, such as the investigation of crystallites and inclusions of minerals, to have an objective capable of magnifying up to 200 or 300 diameters. An instrument with fairly good glasses of these powers, according to the arrangement of object-glasses and eye-pieces, may be had of some London makers for £5. But for some of the most important parts of the microscopical study of rocks a rotating stage is requisite, the presence of which necessarily adds to the cost of the instrument. One of the best microscopes specially adapted for petrographical research is that devised by Mr. A. Dick, and manufactured by Swift & Son, of 81 Tottenham Court Road, London, price £18 without objectives.

Among the indispensable adjuncts are two Nicol-prisms, one (polarizer) to be fitted below the stage, the other (analyser) most advantageously placed over the eye-piece. A quartz-wedge is useful in examination with polarized light. A nose-piece for two objectives, screwed to the foot of the tube, saves time and trouble by enabling the observer at once to pass from a low to a high power. The numerous pieces of apparatus necessary for physiological work are not needed in the examination of rocks and minerals.

3. **Methods of Examination.**—A few hints may be here given for the guidance of the student in making his own microscopic observations, but he must consult some of the special treatises, mentioned on p. 89, for full details.

Reflected Light.—It is not infrequently desirable to observe with the microscope the characters of a rock as an opaque object. This cannot usually be done with a broken fragment of the stone, except of course with very low powers. Hence one of the most useful preliminary examinations of a prepared slice is to place it in the field, and, throwing the mirror out of gear, to converge as strong a light upon it as can be had, short of bright direct sunlight. The observer can then see some way into the rock and observe the relative thicknesses and forms of its constituents. The advantage of this method is particularly noticeable in the case of opaque minerals. The sulphides and iron-oxides so abundant in rocks appear as densely black objects with transmitted light, and show only their external form. But by throwing a strong light upon their surface, we may often discover not only their distinctive colours, but their characteristic internal structure. Titaniferous iron is an admirable example of the advantage of this method. Seen with transmitted light, that mineral appears in black, structureless grains or opaque patches, though frequently bounded by definite lines and angles. But with reflected light, the cleavage and lines of growth of the mineral can then often be clearly seen, and what seemed to be uniform black patches are found in many cases to enclose bright brassy kernels of pyrite. Magnetite also presents a characteristic blue-black colour, which distinguishes it from the other iron-oxides.

Transmitted Light.—It is, of course, with the light allowed to pass through prepared slices that most of the microscopic examination of minerals and rocks is performed. A little experience will show the learner that, in viewing objects in this way, he may obtain somewhat different results from two slices of the same rock according to their relative thinness. In the thicker one, a certain mineral or rock, obsidian for example, will appear perhaps brown or almost black, while in the other what is evidently the same substance may be pale yellow, green, brown, or almost colourless. Triclinic felspars seen in polarized light give only a pale milky light when extremely thin, but present bright chromatic bands when somewhat thicker.

Polarized Light.—By means of polarized light, an exceedingly delicate method of investigation is made available. We use both the Nicol-prisms. If the object be singly-refracting, such as a piece of glass, or an amorphous body, or a crystal belonging to some substance which crystallizes in the isometric or cubic system (or if it be a tetragonal, hexagonal or rhombohedral crystal, cut perpendicular to its principal axis), the light will reach our eye apparently unaffected by the intervention of the object. The field will remain dark when the axes of the two prisms are at right angles (crossed Nicols), in the same way as if no intervening object were there. Such bodies are *isotropic.*[1] In all other cases, the substance is doubly-refracting and modifies the polarized beam of light. On rotating one of the prisms, we perceive bands or flashes of colour, and numerous lines appear which before were invisible. The field no longer remains dark when the two Nicol-prisms are crossed. Such a substance is *anisotropic.*

It is evident, therefore, that we may readily tell by this means whether or not a rock contains any glassy constituent. If it does, then that portion of its mass will become dark when the prisms are crossed, while the crystalline parts which, in the vast majority of cases, do not belong to the cubic system, will remain conspicuous by their brightness. A thin plate of quartz makes this separation of the glassy and crystalline parts of a rock even more satisfactory. It is placed between the Nicol-prisms, which may be so adjusted with reference to it that the field of the microscope appears uniformly violet. The glassy portion of any rock, being singly-refracting or isotropic, placed on the stage will allow the violet light to pass through unchanged, but the crystalline portions, being doubly-refracting or anisotropic, will alter the violet light into other prismatic colours. The object should be rotated in the field, and the eye should be kept steadily fixed upon one portion of the slide at a time, so that any change may be observed. This is an extremely delicate test for the presence of glassy and crystalline constituents.

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[1] But the effect of pressure may give weak colour-tints in glasses and in cubic crystals.

In searching for the crystallographic system to which a mineral in a microscopic slide should be referred, attention is given to the directions in which the mineral placed between crossed Nicols appears dark, or to what are called the directions of its extinction. It is extinguished (that is, the normal darkness of the field between the crossed Nicols is restored) when two of its axes of elasticity for vibrations of light coincide with the principal sections of the two prisms. During a complete rotation of the slide in the field of the microscope the mineral becomes dark in four positions 90° apart, each of which marks that coincidence. When, on the other hand, the prisms are placed parallel to each other, the coincidence of their principal sections with the axes of elasticity in the mineral allows the maximum of light to pass through, which likewise occurs four times in a complete rotation of the mineral. The different crystallographic systems are distinguishable by the relation between their crystallographic axes and their axes of elasticity. By noting this relation in the case of any given mineral (and there are usually sections enough of each mineral in the same rock-slice to furnish the required data) its crystalline system may be fixed. But in many cases it has been found possible to establish characteristic distinctions for individual mineral species, by noting the angle between the direction of their extinction and certain principal faces.

The determination of whether the component grains of a rock belong to uniaxial or biaxial doubly-refracting minerals is a point of much importance, which is effected by means of an achromatic condenser inserted in the aperture of the stage below the slide and suitably adjusted so as to converge the rays of light within the grain or crystal. The Nicols having been crossed, the eye-piece is removed, and the eye when held a little distance from the open end of the tube will perceive a dark bar, ring, or cross move across the field as the stage is rotated, if the mineral examined has been cut at a favourable angle. By the form and behaviour of these indications the uniaxial or biaxial character is made evident.

Pleochroism (*Dichroism*).—Some minerals show a change of colour when a Nicol-prism is rotated below them ; hornblende, for example, exhibiting a gradation from deep brown to dark yellow. A mineral presenting this change is said to be pleochroic (polychroic, dichroic, trichroic). To ascertain the pleochroism of any mineral we may remove the upper polarizing prism (analyser) and leave only the lower (polarizer). If as we rotate the latter, no change of tint can be observed, there is no pleochroic mineral present, or at least none which shows pleochroism at the angle at which it has been bisected in the slice. But in a slice of any crystalline rock, crystals may usually be observed which offer a change of hue as the prism goes round. These are examples of pleochroism. This behaviour may be used to detect the mineral constituents of rocks. Thus the two minerals hornblende and augite, which in so many respects resemble each other, cannot always be distinguished by cleavage angles, in microscopic slices. But as Tschermak pointed out, augite remains passive or nearly so as the lower prism is rotated : it is not pleochroic, or only very feebly so ; while hornblende, on the other hand, especially in its darker varieties, is usually strongly pleochroic. It is to be observed, however, that the same mineral is not always equally pleochroic, and that the absence of this property is therefore less reliable as a negative test, than its presence is as a positive test.

It would be beyond the scope of this volume to enter into the complicated details of the microscopic structure of minerals and rocks. This information must be sought in some of the works specially devoted to it, a few of which are cited on p. 89.

In his examination of rocks with the microscope, the student may find an advantage in propounding to himself the following questions, and referring to the pages here cited.

1st, Is the rock entirely crystalline (pp. 97, 148, 154), consisting solely of crystals of different minerals interlaced; and if so, what are these minerals? 2nd, Is there any trace of a glassy ground-mass or base (pp. 100, 114)? Should this be detected, the rock is certainly of volcanic origin (pp. 162, 171). 3rd, Can any evidence be found of the devitrification of what may have been at one time the glassy basis of the whole rock? This devitrification might be shown by the appearance of numerous microscopic hairs, rods, bundles of feather-like irregular or granular aggregations (p. 115). 4th, In what order did the minerals crystallize? This may often be made out with a microscope, as, for instance, where one mineral is enclosed within another (p. 114).[1] 5th, What is the nature of any alteration which the rock may have undergone? In a vast number of cases the slices show abundant evidence of such alteration: felspar passing into granular kaolin, augite changing into viridite, olivine into serpentine, while secondary calcite, epidote, quartz, and zeolites run in minute veins or fill up interstices of the rock (p. 345). 6th, Is the rock a fragmental one; and if so, what is the nature of its component grains (p. 127)? Is any trace of organic remains to be detected.

§ iv.—General outward or Megascopic (Macroscopic) Characters of Rocks.[2]

1. **Structure.**[3]—The different kinds of rock-structures distinguishable by the unaided eye are denoted either by ordinary descriptive adjectives, or by terms derived from rocks in which the special structures are characteristically developed, such as granitoid, brecciated, shaly. It must be borne in mind, however, that the external character of a rock does not always supply us with its true internal structure, which may be gained only by microscopic examination. This is of course more especially

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[1] It is possible, however, that a crystal enclosed within another may sometimes have crystallized there out of a portion of the surrounding magma of the rock which has been enclosed within the larger crystal (*postea*, p. 303).

[2] The following general text-books on rocks may be referred to: Macculloch, 'A Geological Classification of Rocks,' &c., London, 1821. B. von. Cotta, 'Rocks Classified and Described,' translated by Lawrence, London, 1866. Zirkel, 'Lehrbuch der Petrographie,' two vols. Bonn, 1866. Senft, 'Classification der Felsarten,' Breslau, 1857; 'Die Krystallinischen Felsgemengtheile,' Berlin, 1868. Kenngott, 'Elemente der Petrographie,' Leipz. 1868. A. von Lasaulx, 'Elemente der Petrographie,' Bonn, 1875. Bischof, 'Chemical Geology,' translated for Cavendish Society, 1854-59, and supplement, Bonn, 1871. Roth, 'Allgemeine und Chemische Geologie,' Berlin, 1879. Other works in which the microscopical characters are more specially treated of, are enumerated on p. 108.

[3] In the 3rd edition of Jukes' 'Student's Manual of Geology' (1871), p. 93, it was proposed to reserve the term "Structure" for large features, such as characterise rock-blocks, and to use the term "Texture" for the minuter characters, such as can be judged of in hand specimens. M. De Lapparent makes a similar distinction (Traité, p. 602, *note*). But the practice of using the word structure as it is employed above in the text, has received such a support from the petrographers of Germany that though I still think it would be preferable to distinguish between *texture* and *structure*, I have adopted what has now the sanction of common usage.

true of the close-grained kinds, where to the naked eye no definite structure is discernible. Some of the definitions originally founded on external appearance have been considerably modified by microscopic investigation. Many compact rocks, for instance, have been proved to be wholly crystalline.

The same rock-mass may show very different structures and textures in different parts of its extent. This is true alike of sedimentary and igneous materials. It may be observed even in the several portions of one continuous mass of erupted rock—variations in the rate of cooling, in temperature, and other circumstances have combined to produce sometimes the most extraordinary textural and even structural, as well as chemical and mineralogical contrasts in a boss or sheet of igneous rock.[1] Hence the student must be on his guard against concluding that two portions of rock strikingly unlike each other in outward appearance cannot be portions of one original continuous mass.

Crystalline (Phanerocrystalline), consisting wholly or chiefly of crystalline particles or crystals.[2] Where the individual elements of the rocks are of large size, the structure is *coarse-crystalline* (*granitic*), as in many granites. When the particles are readily visible to the naked eye, and are tolerably uniform in size, as in marble, many granites and dolomites, the rock is said to be granular-crystalline. Successive stages in the diminution of the size of the particles may be traced until these are no longer recognisable with the naked eye, and the structure must then be resolved with the microscope (*fine-crystalline*, *micro-crystalline*, *crypto-crystalline*). Fine-grained rocks may also be called *compact*, though this term is likewise applicable to the more close-grained varieties of the fragmental series. The microscopic characters of such rocks should always be ascertained where possible.[3]

Many crystalline rocks consist not only of crystals, but of a magma or paste, in which the crystalline particles are seen by the naked eye to be imbedded. It is of course impossible, except from analogy, to determine macroscopically what may be the nature of this magma. It may be entirely composed of minute crystals, or may consist of various crystallitic products of devitrification. Its intimate structure can only be ascertained with the microscope. But its existence is often strikingly manifest even to the unassisted eye, for in what are termed "porphyries" it forms a large part of their mass. The term "*ground-mass*" is employed to denote this megascopic matrix. Microscopic examination shows that a ground-mass may consist of minute crystals, or crystallites, or granules and filaments, or glass, or combinations of these in various proportions. (See pp. 109, 117.)

Lithoid, compact and stony in aspect, with no very distinct crystalline structure. The term is especially applied to the devitrified condition of once glassy rocks, such as obsidians, which have assumed the character of perlites or felsites.

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[1] See *postea*, pp. 564, 576; G. F. Becker, *Amer. Journ. Sci.* xxxiii. (1887), p. 50. J. H. L. Vogt, *Geol. Fören. Förhand. Stockholm*, xiii. (1891).

[2] Prof. Rosenbusch proposed the term *holocrystalline* for rocks in which there is no morphous material among the crystalline constituents.

[3] On the crystallization of igneous rocks, see J. P. Iddings, *Bull. Phil. Soc. Washington*, xi. (1889), p. 71.

Granitic (Granitoid), thoroughly crystalline, and consisting of crystals approximately uniform in size, as in granite. This structure is characteristic of many eruptive rocks. Though usually distinctly recognisable by the naked eye ("macromerite" of Vogelsang[1]), it sometimes becomes very fine ("micromerite"), and may be only recognisable with the microscope as thoroughly crystalline (microgranitic); at other times it passes into a porphyritic or porphyroid character by the appearance of large crystals dispersed through a general ground-mass.

Pegmatitic (Pegmatoid, Graphic), exhibiting the peculiar arrangement of crystalline constituents seen in pegmatite or graphic granite (p. 158), where the quartz and felspar have crystallized simultaneously so as to be enclosed within each other. This structure may be seen on a large scale in many massive veins of pegmatite; where it takes an exceedingly minute form it is known as micropegmatitic (Fig. 5). Such microscopic intergrowth of quartz and felspar is characteristic of large masses of eruptive rock (micropegmatite, granophyre).

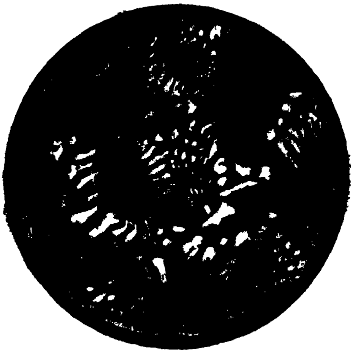

Fig. 5.—Micropegmatitic Structure. Granophyre, Mull. (Magnified.)

Aphanitic, a name given to the very close texture exhibited by some igneous rocks (diabases, diorites) where the component ingredients cannot be determined except with the microscope.

Porphyritic (Porphyroid), composed of a compact or finely crystalline ground-mass, through which larger crystals of earlier consolidation,[2] often of felspar, are dispersed (Fig. 6). This and the granitic structure are the two great structure-types of the eruptive rocks. By far the largest number of these rocks belong to the porphyritic type. Microscopic research has thrown much light on the nature of the ground-mass of porphyritic rocks. Vogelsang proposed to classify these rocks in three divisions:[3] 1st, *Granophyre*, where the ground-mass is a microscopic crystalline mixture of the component minerals with absence or sparing development of an imperfectly individualised magma (see p. 118); 2nd, *Felsophyre*, having usually an imperfectly individualised or felsitic magma for the ground-mass (pp. 117, 119); 3rd, *Vitrophyre*, where the ground-mass is a glassy magma (pp. 114, 120). The second sub-division embraces most of the porphyries, and a very large number of eruptive rocks of all ages.[1]

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[1] *Z. Deutsch. Geol. Ges.* xxiv. p. 534.

[2] Phenocrysts, Iddings, *Bull. Phil. Soc. Washington*, ii. (1889), p. 73.

[3] Vogelsang, *loc. cit.* Compare the classification into *granitoid* and *trachytoid*, p. 155.

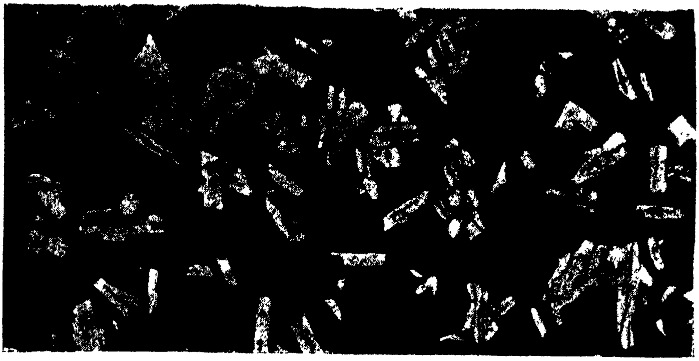

Fig. 6.—Porphyritic Structure. (Nat. size.)

Segregated.—In granite and other crystalline massive rocks, vein-like portions, coarser (or finer) in texture than the rest of the mass, may be observed. These belong to the last phase of consolidation, when segregations from the original molten or viscous magma took place along certain lines or round particular centres, where the individual minerals crystallized out from the general mass. They have been sometimes termed "segregation," or "exudation" veins. They are to be distinguished from the veins, usually of finer and more acid material, which ramify through a mass of igneous rock and probably represent portions of the original molten magma which remained still liquid and were injected into rents of the already consolidated parts. These are the true "contemporaneous veins" (p. 580).

Granular—a somewhat vague term applied to rocks composed of approximately equal grains, which are sometimes worn fragments, as in sandstone, sometimes crystalline particles, as in granite and marble. This texture may become so fine as to pass insensibly into compact.[2] The peculiar granular structure found so abundantly among metamorphic rocks which have been intensely crushed and in which there seems to have been a process of re-crystallization among the powdered particles, has been termed granulitic (p. 119). This word, however, is liable to the objection that in Germany it is applied to rocks bearing that structure while in France it is used for a holocrystalline granite.[3]

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[1] According to Rosenbusch the porphyritic massive rocks are those in which, during the different stages of their production, the same minerals have been formed more than once. *Neues Jahrb.* 1882 (ii.), p. 14.

[2] As applied to massive (eruptive) rocks, Rosenbusch would restrict the term granular to those in which each individual constituent separated out during but one definite stage of the process of rock-building. *Loc. cit.*

[3] Michel-Lévy, *Ann. des Mines*, viii. (1875), p. 387; 'Structure et Classification des Roches Eruptives,' 1889, p. 14.

Vitreous or glassy, having a structure like that of artificial glass, as in obsidian. Among the crystalline rocks there is often present a variable amount of an amorphous ground mass, which may increase until it forms the main part of the substance. The nature of this amorphous portion is described at pp. 114, 120. Its most obvious megascopic condition is that of a volcanic glass. Most vitreous rocks present, even to the naked eye, dispersed grains, crystals, or other enclosures. Under the microscope, they are found to be often crowded with minute crystals and imperfect or incipient crystalline forms (pp. 109, 115). Resinous is the term applied to vitreous rocks having the lustre of pitchstone, and to others which are still less vitreous. Devitrification is the conversion of the vitreous into a crystalline or lithoid structure (pp. 116, 121).

Streaked, arranged in streaky inconstant lines (Germ. *Schlieren*), either parallel or convergent, and often undulating. This structure, conspicuously shown by the lines of flow in vitreous rocks (flow-structure, fluxion-structure, fluidal-structure) is less marked where the materials have assumed definite crystalline forms. It can be seen on a minute scale, however, in many crystalline masses when examined with the microscope (p. 120).

Banded, arranged in parallel bands, distinguished from each other by colour, texture, structure or composition; characteristic of many gneisses, and of jaspers, flints, hälleflintas and other flinty rocks. This term may frequently be applied to the flow-structure of igneous rocks referred to in the previous paragraph, likewise to the segregation veins of eruptive bosses and sheets, and to the parallel arrangement of materials produced in rocks which have under intense mechanical pressure been crushed and sheared. With the naked eye it is often hardly possible to distinguish between the banded structure of devitrified igneous rocks and that resulting from intense mechanical deformation.

Mylonitic, a term introduced to denote the peculiar granular structure of rocks which have undergone intense crushing. The materials have been reduced to minute grains which have not recrystallized as they have done in the granulitic structure. Many remarkable examples of this structure have been observed among the schists of the Scottish Highlands.

Spherulitic, composed of, or containing small globules or spherules which may be colloid and isotropic, or more or less distinctly crystalline, particularly with an internal fibrous divergent structure (Figs. 7, 17). This structure occurs in vitreous rocks, where it is one of the stages of devitrification in obsidian, pitchstone, etc.[1] (p. 121).

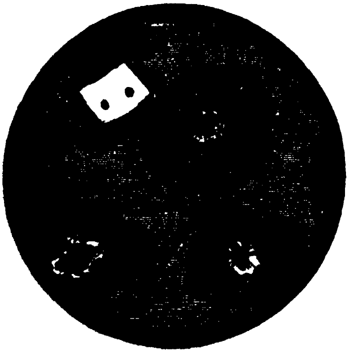

Fig 7.—Spherulitic Structure. (Magnified.)

The term lithophyse has been applied by F. von Richthofen to large bladder-like spherulites wherein interspaces lined with crystals occur between the successive concentric internal layers.[1] Many ancient rhyolites present an aggregate of nodular bodies (Pyromeride) due originally to devitrification and subsequently more or less altered especially by the deposition of silica within them (*postea*, p. 161).

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[1] On the constitution and origin of spherulite in acid eruptive rocks, see Whitman.

Orbicular structure is one in which the component minerals of a rock have crystallized in such a way as to form spheroidal aggregations sometimes with an internal radial or concentric grouping. It is typically seen in the napoleonite or ball-diorite (kugeldiorite, orbicular diorite, p. 165) of Corsica (Fig. 8), but occurs in other rocks, sometimes even in granite.

Fig. 8.—Orbicular Structure. Napoleonite, Corsica. (Nat. size.)

Perlitic (Figs. 9 and 20), having the structure of the rock formerly termed perlite, wherein between minute rectilinear fissures the substance of the mass has assumed, during the contraction resulting from cooling, a finely globular character, not unlike the spheroidal structure seen in weathered basalt which is also a phenomenon of contraction during the cooling and consolidation of an igneous rock.

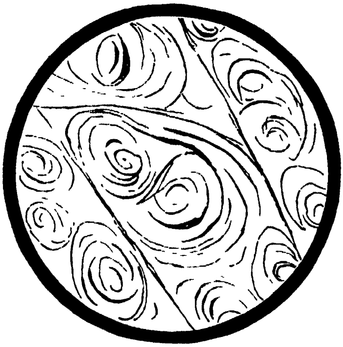

Fig. 9.—Perlitic Structure. (Magnified.)

Cross, *Phil. Soc. Washington*, xi. p. 411 (1891), and J. P. Iddings, *op. cit.* p. 445. Quartz assumes in some rocks (*e.g.* banded eurites) a finely globular structure which was developed before the cessation of the motion that produced flow-structure, and which, according to M. Michel-Lévy, may be regarded as connecting the colloid and crystallized conditions of silica. *Bull. Soc. Géol. France* (3), v. p. 140.

[1] *Jahrb. K. K. Geol. Reichsanst*, 1860, p. 180. See Iddings, *7th Ann. Rep. U.S. Geol. Surv.* (1885-86), p. 249. *Amer. Journ. Sci.* xxxiii. (1887), p. 36.

Horny, flinty, having a compact, homogeneous, dull texture, like that of horn or flint, as in chalcedony, jasper, flint, and many hälleflintas and felsites.

Cavernous (porous), containing irregular cavities due, in most cases, to the abstraction of some of the minerals; but occasionally, as in some limestones (sinters), dolomites and lavas, forming part of the original structure of the rock.

Cellular.—Many lavas, ancient and modern, have been saturated with steam at the time of their eruption, and in consequence of the segregation and expansion of this imprisoned vapour, have had spherical cavities developed in their mass. When this cellular structure is marked by comparatively few and small holes, it may be called **vesicular**; where the rock consists partly of a roughly cellular, and partly of a more compact substance intermingled, as in the slag of an iron furnace, it is said to be **slaggy**; portions where the cells occupy about as much space as the solid part, and vary much in size and shape, are called **scoriaceous**, this being the character of the rough clinker-like scoriæ of recent lava-streams; when the cells are so much more numerous than the solid part, that the stone would almost or quite float on water, the structure is called **pumiceous**, the term *pumice* being applied to the froth-like part of obsidian. As the cellular structure can only be developed while the rock is still liquid, or at least viscid, and as, while in this condition, the mass is often still moving away from its point of emission, the cells are not infrequently elongated in the direction of movement. Subsequently, water infiltrating through the rock, deposits various mineral substances (calcite, quartz, chalcedony, zeolites, etc.) from solution, so that the flattened and elongated almond-shaped cells are eventually filled up. A cellular rock which has undergone this change is said to be an **amygdaloid**, or **amygdaloidal**, and the almond-like kernels are known as **amygdales** (Fig. 10). Where the cells or cavernous spaces of a rock are lined with crystals and empty inside they are said to be **druses** or **drusy cavities**.

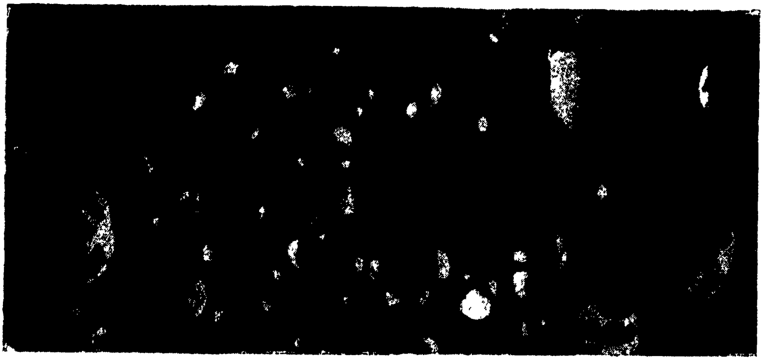

Fig. 10.—Amygdaloidal Structures; Porphyrite, Old Red Sandstone, Ayrshire. (Nat. size.)

Cleaved, having a fissile structure superinduced by pressure and known as cleavage (see p. 312, 545). The planes of cleavage are independent of those of bedding, though they may coincide with them. A cleaved structure is best seen in fine-grained material, and is typically developed in roofing-slate, but it may occur in any compact igneous rock.

Foliated, consisting of minerals that have crystallized in approximately parallel, lenticular, and usually wavy layers or folia. Rocks of this kind commonly contain layers of mica, or of some equivalent readily cleavable mineral, the cleavage-planes of which coincide generally with the planes of foliation. Gneiss, mica-schist and talc-schist are characteristic examples. So distinctive, indeed, is this structure in schists, that it is often spoken of as schistose. In gneiss, it attains its most massive form; in chlorite-schist and some other schists, it becomes so fine as to pass into a kind of minutely scaly texture, often only perceptible with the microscope, the rock having on the whole a massive structure.

Fibrous, consisting of one or more minerals composed of distinct fibres. Sometimes the fibres are remarkably regular and parallel, as in fibrous gypsum, and veins of chrysotile, fibrous aragonite or calcite (satin-spar); in other instances, they are more tufted and irregular, as in asbestos and actinolite-schist.

Clastic, fragmental, composed of detritus (p. 121). Rocks possessing this character have, in the great majority of cases, been formed in water, and their component fragments are usually more or less rounded or water-worn. Different names are applied, according to the form or size of the fragments. Brecciated, composed, like a breccia, of angular fragments, which may be of any degree of coarseness. Agglomerated, consisting of large, roughly rounded and tumultuously grouped blocks, as in the agglomerate filling old volcanic funnels. Conglomerated (Conglomeratic), made up of well-rounded blocks or pebbles; rocks having this character have been formed by and deposited in water. Pebbly, containing dispersed water-worn pebbles, as in many coarse sandstones, which thus by degrees pass into conglomerates. Psammitic, or sandstone-like, composed of rounded grains, as in ordinary sandstone: when the grains are larger (often sharp and somewhat angular) the rock is gritty, or a grit. Muddy (pelitic), having a texture like that of dried mud. Cryptoclastic or compact, where the grains are too minute to reveal to the naked eye the truly fragmental character of the rock, as in fine mudstones and other argillaceous deposits.

Concretionary, containing, or consisting of mineral matter, which has been collected, either from the surrounding rock or from without, round some centre, so as to form a nodule or irregularly shaped lump. This aggregation of material is of frequent occurrence among water-formed rocks, where it may be often observed to have taken place round some organic centre, such as a leaf, cone, shell, fish-bone, or other relic of plant or animal. (Book IV. Part I.) Among the most frequent minerals found in concretionary forms as constituents of rocks, are calcite, siderite, pyrite, marcasite, and various forms of silica. In a true concretion, the material at the centre has been deposited first, and has increased by additions from without, either during the formation of the enclosing rock, or by subsequent concentration and aggregation. Where, on the other hand, cavities and fissures have been filled up by the deposition of materials on their walls, and gradual growth inward, the result is known as a secretion. Amygdales and the successive coatings of mineral veins are examples of the latter process.

Septarian—a structure often exhibited by concretions of limestone and clay-ironstone which in consolidating have shrunk and cracked internally. These shrinkage-cracks radiate in an irregular way from the middle towards the circumference, but die out before reaching the latter (Fig. 26). Usually they have been filled with some subsequently infiltrated mineral, notably calcite.

Oolitic, a structure like fish-roe, formed of spherical grains, each of which has an internal radiating and concentric structure, and often possesses a central nucleus of some foreign body. This structure is specially found among limestones (see p. 150). When the grains are as large as peas, the structure is termed pisolitic.

Various structures which affect large masses of rock rather than hand-specimens will be found described in Book IV. But a few of the more important may be included here.

Massive, unstratified, having no arrangement in definite layers or strata. Lava, granite, and generally all crystalline rocks which have been erupted to the surface, or have solidified below from a state of fusion are massive rocks.

Stratified, bedded, composed of layers or beds lying parallel to each other, as in shale, sandstone, limestone, and other rocks which have been deposited in water. Successive streams of lava, poured one upon another, have also a bedded arrangement. Laminated, consisting of fine, leaf-like strata or laminæ; this structure being characteristically exhibited in shales, is sometimes also called shaly.

Jointed, traversed by the divisional planes termed Joints which are fully treated of in Book IV. Part II.

Columnar, divided into prismatic joints or columns. This structure is typically represented among the basalts and other basic lavas (p. 529 and Figs. 230-2), but it may also be observed as an effect of contact-metamorphism among stratified rocks which have been invaded by intrusive masses (p. 599).

2. **Composition.**—Before having recourse to chemical or microscopic analysis, the geologist can often pronounce as to the general chemical or mineralogical nature of a rock. Most of the terms which he employs to express his opinion are derived from the names of minerals, and in almost all cases are self-explanatory. The following examples may suffice. Calcareous, consisting of or containing carbonate of lime. Argillaceous, consisting of or containing clay. Felspathic, having some form of felspar as a main constituent. Siliceous, formed of or containing silica; usually applied to the chalcedonic forms of this cementing oxide. Quartzose, containing or consisting entirely of some form of quartz.

Carbonaceous, containing coaly matter, and hence usually associated with a dark colour. Pyritous, containing diffused disulphide of iron. Gypseous, containing layers, nodules, strings or crystals of calcium-sulphate. Saliferous, containing beds of, or impregnated with rock-salt. Micaceous, full of layers of mica-flakes.

As rocks are not definite chemical compounds, but mixtures of different minerals in varying proportions, they exhibit many intermediate varieties. Transitions of this kind are denoted by such phrases as "granitic gneiss," that is, a gneiss in which the normal foliated structure is nearly merged into the massive structure of granite; "argillaceous limestone"—a rock in which the limestone is mixed with clay; "calcareous shale"—a fissile rock, consisting of clay with a proportion of lime. It is evident that such rocks may graduate so insensibly into each other, that no sharp line can be drawn between them either in the field or in their terminology.

As already alluded to, and as will be more fully explained in later pages, the progress of research goes to show that even in the same mass of eruptive rock considerable differences of chemical composition may be found. These differences seem to point to some separation of the constituents, by gravity or otherwise, before consolidation. Thus the picrite of Bathgate shades upwards into a rock in which the heavy magnesian silicates are replaced in large measure by felspars.[1] Mr. Iddings has recently called attention to some remarkable gradations of composition among the volcanic rocks of the Tewar mountains, New Mexico, where he believes a series of intermediate varieties to be traceable from obsidian at the one end to basalt at the other.[2] A remarkable instance of a similar kind is described by Mr. Teall and Mr. Dakyns from the Scottish Highlands.

3. **State of Aggregation.**—The hardness or softness of a rock, in other words, its induration, friability, or the degree of aggregation of its particles, may be either original or acquired. Some rocks (sinters, for example) are soft at first and harden by degrees; the general effect of exposure, however, is to loosen the cohesion of the particles of rocks. A rock which can easily be scratched with the nail is almost always much decomposed, though some chloritic and talcose schists are soft enough to be thus affected. Compact rocks which can easily be scratched with the knife, and are apparently not decomposed, may be fine-grained limestones, dolomites, ironstones, mudstones, or some other simple rocks. Crystalline rocks, except limestone cannot, as a rule, be scratched with the knife unless considerable force be used. They are chiefly composed of hard silicates, so that when an instance occurs where a fresh specimen can be easily scratched, it will usually be found to be a limestone (pp. 82, 139, 149). The ease with which a rock may be broken is the measure of its frangibility. Most rocks break most easily in one direction; attention to this point will sometimes throw light upon their internal structure.

Fracture is the surface produced when a rock is split or broken, and depends for its character upon the texture of the mass. Finely granular, compact rocks are apt to break with a splintery fracture where wedge-shaped plates adhere by their thicker ends to, and lie parallel with the general surface. When the rock breaks off into concave and convex rounded shell-like surfaces, the fracture is said to be conchoidal, as may be seen in obsidian and other vitreous rocks, and in exceedingly compact limestones. The fracture may also be foliated, slaty, or shaly, according to the structure of the rock. Many opaque, compact rocks are translucent on the thin edges of fracture, and afford there, with the aid of a lens, a glimpse of their internal composition. A rock is said to be flinty, when it is hard, close-grained, and breaks with a smooth or conchoidal fracture like flint; friable, when it crumbles down like dry clay or chalk; plastic, when, like moist clay, it can be worked into shapes; pulverulent, when it falls readily to powder; earthy, when it is decomposed into loam or earth; incoherent or loose, when its particles are quite separate, as in dry blown sand.

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[1] *Trans. Roy. Soc. Edin.* vol. xxix. (1879), p. 504.

[2] *Bull. U. S. Geol. Surv.* No. 66 (1890), *Bull. Phil. Soc. Washington*, xi. (1890), pp. 65, 191, and *postea*, pp. 269, 576. Teall and Dakyns, *Quart. Journ. Geol. Soc.* 1892.

4. **Colour and Lustre.**—These characters vary so much, even in the same rock, according to the freshness of the surface examined, that they possess but a subordinate value. Nevertheless, when cautiously used, colour may be made to afford valuable indications as to the probable nature and composition of rocks. It is, in this respect, always desirable to compare a freshly-broken with a weathered piece of the rock.[1]

White indicates usually the absence or a comparatively small amount of the heavy metallic oxides, especially iron. It may either be the original colour, as in chalk and calc-sinter, or may be developed by weathering, as in the white crust on flints and on many porphyries. *Grey* is a frequent colour of rocks which, if quite pure, would be white, but which acquire a greyish tint by admixture of dark silicates, organic matter, diffused pyrites, &c. *Blue*, or *bluish-grey* is a characteristic tint of rocks through which iron-disulphide is diffused in extremely minute subdivision. But as a rule it rapidly disappears from such rocks on exposure, especially where they contain organic matter also. The stiff blue clay of the sea-bottom which is coloured by iron-disulphide becomes reddish-brown when dried, and then shows no trace of sulphide.[2] *Black* may be due either to the presence of carbon (when weathering will not change it much), or to some iron-oxide (magnetite chiefly), or some silicate rich in iron (as hornblende and augite). Many rocks (basalts and melaphyres particularly) which look quite black on a fresh surface, become red, brown or yellow on exposure, black being comparatively seldom a weathered colour. *Yellow* (or *Orange*), as a dull earthy colouring matter, almost always indicates the presence of hydrated peroxide of iron. In modern volcanic districts it may be due to iron-chloride, sulphur, &c. Bright, metallic, gold-like yellow is usually that of iron-disulphide. *Brown* is the normal colour of some carbonaceous rocks (lignite), and ferruginous deposits (bog-iron-ore, clay-ironstone, &c.) It very generally, on weathered surfaces, points to the oxidation and hydration of minerals containing iron. *Red*, in the vast majority of cases, is due to the presence of anhydrous peroxide of iron. This mineral gives dark blood-red to pale flesh-red tints. As it is liable, however, to hydration, these hues are often mixed with the brown, orange and yellow colours of limonite.[1] *Green*, as the prevailing tint of rocks, occurs amongst schists, when its presence is usually due to some of the hydrous magnesian silicates (chlorite, talc, serpentine). It appears also among massive rocks, especially those of older geological formations, where hornblende, olivine, or other silicates have been altered. Among the sedimentary rocks, it is principally due to ferrous silicate (as in glauconite). Carbonate of copper colours some rocks emerald- or verdigris-green. The mottled character so common among many stratified rocks is frequently traceable to unequal weathering, some portions of the iron being more oxidized than others; while some, on the other hand, become deoxidized from the reducing action of decaying organic matter, as in the circular green spots so often found among red strata.

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[1] Alterations of the colours of minerals and rocks are effected by heat and even by sunlight. See Janettaz, *Bull. Soc. Géol.* xxix. (1872), p. 300.

[2] J. Y. Buchanan, *Brit. Assoc.* 1881, p. 584.

Lustre, as an external character of rocks, does not possess the value which it has among minerals. In most rocks, the granular texture prevents the appearance of any distinct lustre. A completely *vitreous* lustre without a granular texture, is characteristic of volcanic glass. A *splendent semi-metallic* lustre may often be observed upon the foliation planes of schistose rocks and upon the laminæ of micaceous sandstones. As this silvery lustre is almost invariably due to the presence of mica, it is commonly called distinctively *micaceous*. A *metallic* lustre is met with sometimes in beds of anthracite; more usually its occurrence among rocks indicates the presence of metallic oxides or sulphides. A *resinous* lustre is characteristic of many pitchstones. *Lustre-mottling* is a term applied to the interrupted sheen on the cleavage faces of minerals which have enclosed much smaller crystals or grains of other minerals. It is well seen on the surfaces of some of the constituents of serpentine rocks.

5. **Feel and Smell.**—These minor characters are occasionally useful. By the feel of a mineral or rock is meant the sensation experienced when the fingers are passed across its surface. Thus hydrous magnesian silicates have often a marked soapy or greasy feel. Some sericitic mica-schists show the same character. Trachyte received its name from its characteristic rough or harsh feel. Some rocks adhere to the tongue, a quality indicative of their tendency to absorb water.

Smell.—Many rocks, when freshly broken, emit distinctive odours. Those containing volatile hydrocarbons give sometimes an appreciable *bituminous* odour, as is the case with certain eruptive rocks, which in central Scotland have been intruded through coal-seams and carbonaceous shales. Limestones have often a *fetid* odour; rocks full of decomposing sulphides are apt to give a *sulphurous* odour; those which are highly siliceous yield, on being struck, an *empyreumatic* odour. It is characteristic of argillaceous rocks to emit a strong earthy smell when breathed upon.

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[1] See I. C. Russell, *Bull. U. S. Geol. Surv.* No. 52 (1889).

6. **Specific Gravity.**—This is an important character among rocks as well as among minerals. It varies from 0·6 among the hydrocarbon compounds to 3·1 among the basalts. As already stated, the average specific gravity of the rocks of the earth's crust may be taken to be about 2·5, or from that to 3·0. Instruments for taking the specific gravity of rocks have been already (p. 85) referred to.

7. **Magnetism** is so strongly exhibited by some crystalline rocks as powerfully to affect the magnetic needle, and to vitiate observations with this instrument. It is due to the presence of magnetic iron, the existence of which may be shown by pulverising the rock in an agate mortar, washing carefully the triturated powder, and drying the heavy residue, from which grains of magnetite or of titaniferous magnetic iron may be extracted with a magnet. This may be done with any basalt (p. 86). A freely swinging magnetic needle is of service, as by its attraction or repulsion, it affords a delicate test for the presence of even a small quantity of magnetic iron.

§ v. Microscopic Characters of Rocks.

No department of Geology has been more advanced in recent years than Lithology, and this has been mainly due to the introduction of the microscope as an instrument for investigating minute internal structure. As far back as the year 1827, a method of making thin transparent sections of fossil wood, and mounting them on glass with Canada balsam, had been devised by William Nicol of Edinburgh, and was employed by Henry Witham in his 'History of Fossil Vegetables.'[1]

It was not, however, until 1856 that Mr. H. C. Sorby, applying this method to the investigation of minerals and rocks, showed how many and important were the geological questions on which it was calculated to shed light.[2] Reference will be made in subsequent pages to the remarkable results then announced by him. To the publication of his memoir the subsequent rapid development of the microscopic study of rocks may be distinctly traced. The microscopic method of analysis is now in use in every country where attention is paid to the history of rocks.[3]

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[1] Small 4to, Edinburgh, 1831. This work, though dedicated to Nicol, does not distinctly recognise him as the actual inventor of the process of slicing mineral substances for microscopic investigation. All that was original in Witham's researches he owed either directly or indirectly to Nicol.

[2] *Brit. Assoc.* 1856, Sect. p. 78. *Quart. Journ. Geol. Soc.* xiv. 1858. *Micr. Journ.* xvii. (1877), p. 113.

[3] Among the best text-books on this subject the following may be mentioned:—'Mikroskopische Beschaffenheit der Mineralien und Gesteine,' F. Zirkel, 1 vol. 1873. 'Mikroskopische Physiographie der Mineralien und Gesteine,' H. Rosenbusch, 2 vols. 2nd Edit. 1885-87, and the English translation of the first volume quoted on p. 89; likewise the Tables translated by F. H. Hatch quoted on p. 90. 'Elemente der Petrographie,' A. von Lasaulx, 1875. 'Minéralogie micrographique: roches éruptives françaises,' Fouqué and Michel-Lévy, 2 vols. 4to, Paris, 1879. 'Microscopical Petrography,' Zirkel, being vol. vi. of the *Geol. Explor. of 40th Parallel*, Washington, 1876. 'British Petrography,' J. J. H. Teall, London, 1888. 'Les Minéraux des Roches,' Michel-Lévy and Lacroix, Paris, 1888.

In § iii. p. 90 information has been given regarding the preparation of sections of rocks for microscopical examination, the methods of procedure in the practice of this part of geological research, and some of the terms employed in the following pages.

1. *Microscopic Elements of Rocks.*

Rocks when examined in thin sections with the microscope are found to be composed of or to contain various elements, of which the more important are, 1st, crystals, or crystalline substances; 2nd, glass; 3rd, crystallites; 4th, detritus.

A. CRYSTALS OR CRYSTALLINE SUBSTANCES.—Rock-forming minerals, when not amorphous, may be either crystallized in their proper crystallographic forms (idiomorphic), or while possessing a crystalline internal structure, may present no definite external geometrical form (allotriomorphic, p. 118). The latter condition is more prevalent, seeing that minerals have usually been developed round and against each other, thus mutually hindering the assumption of determinate crystallographic contours. Other causes of imperfection are fracture by movement in the original magma of the rock, and partial solution in that magma (Fig. 12), as in the corroded quartz of quartz-porphyries and rhyolites, and the hornblende crystals of basalts. The ferro-magnesian minerals of earlier consolidation among basalts and andesites, are sometimes surrounded with a dark shell called the corrosion-zone. In some rocks, such as granite, the thoroughly crystalline character of the component ingredients is well marked, yet they less frequently present the definite isolated crystals so often to be observed in porphyries and in many old and modern volcanic rocks. Among thoroughly crystalline rocks, good crystals of the component minerals may be obtained from fissures and cavities in which there has been room for their formation. It is in the "drusy" cavities of granite, for example, that the well-defined prisms of felspar, quartz, mica, topaz, beryl and other minerals are found. Successive stages in order of appearance or development can readily be observed among the crystals of rocks. Some appear as large, but frequently broken, or corroded forms. These have evidently been formed first. Others are smaller but abundant, usually unbroken, and often disposed in lines. Others have been developed by subsequent alteration within the rock.[1]

A study of the internal structure of crystals throws light not merely

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The volumes for the last fifteen or twenty years of the *Quarterly Journal of the Geological Society*, *Geological Magazine*, *Neues Jahrbuch für Mineralogie, &c.*, *Zeitschrift der Deutschen Geologischen Gesellschaft*, *Bulletin de la Société géologique de France*, *Jahrbuch der K. K. Geologischen Reichsanstalt* (*Vienna*), contain numerous papers on the microscopic structure of rocks. Rutley's 'Study of Rocks,' 1879, and his 'Rock-forming Minerals,' 1888; Cole's 'Aids in Practical Geology,' 1891; and Hatch's 'Petrology—Igneous Rocks,' 1891, are useful handbooks. The manual of Rosenbusch and the work of Fouqué and Michel-Lévy, contain a tolerably ample bibliography of the subject, to which the student is referred. The titles of some of the more important memoirs which have recently appeared will be given in footnotes.

[1] Fouqué and Michel-Lévy, 'Min. Micrograph.' p. 151.

on their own genesis, but on that of the rocks of which they form part, and is therefore well worthy of the attention of the geologist. That many apparently simple crystals are in reality compound, may not infrequently be detected by the different condition of weathering in the two opposite parts of a twin on an exposed face of rock. The internal structure of a crystal modifies the action of solvents on its exterior (*e.g.* weathered surfaces of calcite, aragonite and felspars). Crystals may occasionally be observed built up of rudimentary "microlites," as if these were the simplest forms in which the molecules of a mineral begin to appear (p. 115).

A microscopic examination of some rocks shows that a subsequent or secondary growth of different minerals has taken place after their original crystalline form was complete. These later additions are in optical continuity with the original crystal, and sometimes have taken place even upon worn or imperfect forms. They may be occasionally detected among the silicates of igneous rocks, and also even among the sandgrains of sandstones which have thus had their rounded forms converted into crystallographic faces.[1]

Crystalline minerals are seldom free from extraneous *inclusions.* These are occasionally large enough to be readily seen by the naked eye. But the microscope reveals them in many minerals in almost incredible quantity. They are, α, vesicles containing gas; β, vesicles containing liquid; γ, globules of glass or of some lithoid substance; δ, crystals; ε, filaments, or other indefinitely-shaped pieces, patches, or streaks of mineral matter.

α. Gas-filled cavities—are most frequently globular or elliptical, and appear to be due to the presence of gas or steam in the crystal at the time of consolidation. Zirkel estimates them at 360,000,000 in a cubic millimetre of the hauyne from Melfi.[2] In some instances the cavity has a geometric form belonging to the crystalline system of the enclosing mineral. Such a space defined by crystallographic contours is a *negative crystal.* A cavity filled with gas contains no bubble, and its margin is marked by a broad dark band. The usual gas is nitrogen, with traces of oxygen and carbon-dioxide; sometimes it is entirely carbon-dioxide or hydrogen and hydrocarbons.

β. Vesicles containing liquid (and gas).—As far back as the year 1823, Brewster studied the nature of certain fluid-bearing cavities in different minerals.[3] The first observer who showed their important bearing on geological researches into the origin of crystalline rocks was Mr. Sorby, in whose paper, already cited, they occupy a prominent place. Vesicles entirely filled with liquid are distinguished by their sharply-defined and narrow black borders. Vesicular spaces containing fluid may be noticed in many artificial crystals formed from aqueous solutions (crystals of common salt show them well) and in many minerals of crystalline rocks. They are exceedingly various in form, being branching, curved, oval, or spherical, and sometimes assuming as negative crystals a geometric form, like that characteristic of the mineral in which they occur, as cubic in rock-salt and hexagonal in quartz. They also vary greatly in size. Occasionally in quartz, sapphire, and other minerals, large cavities are readily observable with the naked eye. But they may be traced with high magnifying powers down to less than $\frac{1}{10000}$ of an inch in diameter. Their proportion in any one crystal ranges within such wide limits, that whereas in some crystals of quartz few may be observed, in others they are so minute and abundant that many millions must be contained in a cubic inch. The fluid present is usually water, frequently with saline solutions, particularly chloride of sodium or of potash, or sulphates of potash, soda, or lime. Carbon-dioxide may be present in the water; sometimes the cavities are partially occupied with it in liquid form, and the two fluids, as originally observed by Brewster, may be seen in the same cavity unmingled, the carbon-dioxide remaining as a freely moving globule within the carbonated water. Cubic crystals of chloride of sodium may be occasionally observed in the fluid, which must in such cases be a saturated solution of this salt (Fig. 11, lowest figure in Column A). Usually each cavity contains a small globule or bubble, sometimes stationary, sometimes movable from one side or end of the cavity to the other, as the specimen is turned. With a high magnifying power, the minuter bubbles may be observed to be in motion, sometimes slowly pulsating from side to side, or rapidly vibrating like a living organism. The cause of this trepidation, which resembles the so-called "Brownian movements," has been plausibly explained by the incessant interchange of the molecules from the liquid to the vaporous condition along the surface where vapours and liquid meet—an interchange which, though not visible on the large bubbles, makes itself apparent in the minute examples, of which the dimensions are comparable to those of the intermolecular spaces.[1] The bubble may be made to disappear by the application of heat.

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[1] H. C. Sorby, Presidential Address, *Geol. Soc.* 1880, p. 62. R. D. Irving and C. R. Van Hise 'On secondary enlargements of Mineral Fragments in certain rocks.' *Bull. U. S. Geol. Surv.* No. 8 (1884). J. W. Judd. *Quart. Journ. Geol. Soc.* xlv. (1889), p. 175.

[2] 'Mik. Beschaff.' p. 86.

[3] *Edin. Phil. Journ.* ix. p. 94. *Trans. Roy. Soc. Edin.* x. p. 1. See also W. Nicol, *Edin. New Phil. Journ.* (1828), v. p. 94; De la Vallée Poussin and Renard, *Acad. Roy. Belg.* 1876, p. 41; Hartley, *Journ. Chem. Soc.* ser. 2, xiv. 137; ser. 3, ii. p. 241; *Microscop. Journ.* xv. p. 170; *Brit. Assoc.* 1877, Sect. p. 232.

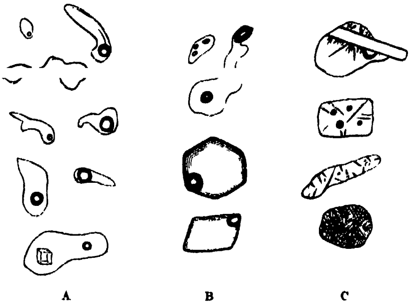

Fig. 11.—Cavities in Crystals, highly magnified; A, Liquid Inclusions; B, Glass Inclusions; C, Cavities showing the devitrification of the original glass by the appearance of crystals, &c., until in the lowest figure a stony or lithoid product is formed.

With regard to the origin of the bubble, Sorby pointed out that it can be imitated in artificial crystals, in which he explained its existence by diminution of volume of the liquid owing to a lowering of temperature after its enclosure. By a series of experiments he ascertained the rate of expansion of water and saline solutions up to a temperature of 200° C. (392° Fahr.), and calculated from them the temperature at which the liquid in crystals would entirely fill its enclosing cavities. Thus, in the nepheline of the ejected blocks of Monte Somma, he found that the relative size of the vacuities was about ·28 of the fluid, and assuming the pressure under which the crystals were formed to have been not much greater than sufficient to counteract the elastic force of the vapour, he concluded that the nepheline may have been formed at a temperature of about 340° C. (644° Fahr.), or a very dull red heat, only just visible in the dark. He estimated also from the fluid cavities in the quartz of granite that this rock has probably consolidated at somewhat similar temperatures, under a pressure sometimes equal to that of 76,000 feet of rock.[1] Zirkel, however, has pointed out that even in contiguous cavities, where there is no evidence of leakage through fine fissures, the relative size of the vacuole varies within very wide limits, and in such a manner as to indicate no relation whatever to the dimensions of the enclosing cavities. Had the vacuole been due merely to the contraction of the liquid on cooling, it ought to have always been proportionate to the size of the cavity.[2]

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[1] Charbonelle and Thirion, *Rev. Quest. Scientif.* vii. (1880) 43. On the critical point of water, &c., in these cavities see Hartley, *Journ. Chem. Soc.* ser. 3, vol. ii. p. 241. *Pop. Sci. Rev.* new ser. i. p. 119.

MM. De la Vallée Poussin and Renard, attacking the question from another side, measured the relative dimensions of the vesicle and of its enclosed water and cube of rock-salt, as contained in the quartziferous diorite of Quenast in Belgium. The temperature at which the ascertained volume of water in the cavity would dissolve its salt was found by calculation to be 307° C. (520° Fahr.) But as the law of the solubility of common salt has not been experimentally determined for high temperatures, this figure can only be accepted provisionally, though other considerations go to indicate that it is probably not far from the truth. Assuming then that this was the temperature at which the vesicle was formed, these authors proceed to determine the pressure necessary to prevent the complete vaporization of the water at that temperature, and obtain, as the result, a pressure of 87 atmospheres, equal to 84 tons per square foot of surface.[3] That many rocks were formed under great pressure is well shown by the liquid carbon-dioxide in the pores of their crystals.

Although, in almost all cases, the liquid inclusions are to be referred to the conditions under which the mineral crystallized out of the original magma, they may be exceptionally developed long subsequently, either in one of the original minerals during decomposition, or in a mineral of secondary origin, such as quartz of subsequent introduction.[4]

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[1] Sorby, *Q. J. Geol. Soc.* xiv. pp. 480, 493.

[2] 'Mik. Beschaff.' p. 46.

[3] 'Mémoire sur les Roches dites Plutoniennes de la Belgique,' De la Vallée Poussin and A. Renard. *Acad. Roy. Belg.* 1876, p. 41. See also Ward, *Q. J. Geol. Soc.* xxxi. p. 568, who believed that the granites of Cumberland consolidated at a maximum depth of 22,000 to 30,000 feet.

[4] See Whitman Cross on the development of liquid inclusions in plagioclase during the

Liquid inclusions may be dispersed at random through a crystal, or as in the quartz of granite, gathered in intersecting planes (which look like fine fissures and which may sometimes have become real fissures, owing to the line of weakness caused by the crowding of the cavities), or disposed regularly in reference to the contour of the crystal. In the last case they are sometimes confined to the centre, sometimes arranged in zones along the lines of growth of the crystal.[1] They are specially conspicuous in the quartz of granite and other massive rocks, as well as of gneiss and mica-schist; also in felspars, topaz, beryl, augite, nepheline, olivine, leucite and other minerals.

γ. Inclusions of glass or of some lithoid substance.—In many rocks which have consolidated from fusion, the component crystals contain globules or irregularly shaped enclosures of a vitreous nature (Fig. 11, Column B). These enclosures are analogous to the fluid-inclusions just described. They are portions of the original glassy magma out of which the minerals of the rock crystallized, as portions of the mother-liquor are enclosed in artificially formed crystals of common salt. That magma is in reality a liquid at high temperatures, though at ordinary temperatures it becomes a solid. At first, these glass-vesicles may be confounded with the true liquid-cavities, which in some respects they closely resemble. But they may be distinguished by the immobility of their bubbles, of which several are sometimes present in the same cavity; by the absence of any diminution of the bubbles when heat is applied; by the elongated shape of many of the bubbles; by the occasional extrusion of a bubble almost beyond the walls of the vesicle; by the usual pale greenish or brownish tint of the substance filling the vesicle, and its identity with that forming the surrounding base or ground-mass in which the crystals are imbedded; and by the complete passivity of the substance in polarized light (see p. 94).

Glass inclusions occur abundantly in some minerals, aggregated in the centre of a crystal or ranged along its zones of growth with singular regularity. They appear in felspars, quartz, leucite, and other crystalline ingredients of volcanic rocks, and of course prove that in such positions these minerals, even the refractory quartz, have undoubtedly crystallized out of molten solutions.

In inclusions of a truly vitreous nature, traces of devitrification may not infrequently be seen. In particular, microscopic crystallites (p. 115) make their appearance, like those in the ground-mass of the rock. Sometimes the inclusions, like the general ground-mass, have an entirely stony character (Fig. 11, C). This may be well observed in those which have not been entirely separated from the surrounding ground-mass, but are connected with it by a narrow neck at the periphery of the enclosing crystal. In some granites and in elvans, the quartz by irregular contraction, while still in a plastic state, appears to have drawn into its substance

decomposition of the gneiss of Brittany. Tschermak's *Min. Mittheil.* 1880, p. 369; also G. F. Becker, 'Geology of Comstock Lode.' *U. S. Geol. Surv.* 1882, p. 371.

[1] The way in which vesicles, enclosed crystals, &c., are grouped along the zones of growth of crystals is illustrated in Fig. 12.

portions of the surrounding already lithoid base;[1] but this appearance may sometimes be due to irregular corrosion of the crystals by the magma.[2]

δ. Crystals and crystalline bodies.—Many component minerals of rocks contain other minerals (Fig. 12). These occur sometimes as perfect crystals, more usually as what are termed microlites (p. 115). Like the glass-inclusions, they tend to range themselves in lines along the successive zones of growth in the enclosing mineral. Microlites are of frequent occurrence in leucite, garnet, augite, hornblende, calcite, fluorite, &c. From the fact that microlites of the easily fusible augite are, in the Vesuvian lavas, enclosed within the extremely refractory leucite, it was supposed that the relative order of fusibility is not always followed in the microlites and enveloping crystals. But this has been satisfactorily explained by Fouqué and Michel-Lévy, who have shown experimentally that leucite, when crystallizing from fusion, tends to catch up inclusions of the surrounding glass, which, should the glass be pyroxenic, may assume the form of augite.[3]

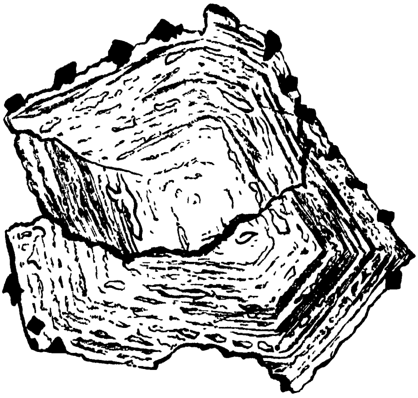

Fig. 12.—Section of a fractured and corroded Augit crystal from a dyke, Crawfordjohn, Lanarkshire (magnified), showing lines of growth with vesicles and magnetite crystals.

ε. Filaments, streaks, patches, discolorations.—Besides the enclosures already enumerated, crystals likewise frequently enclose irregular portions of mineral matter, due to alteration of the original substance of the minerals or rocks. Thus tufts and vermicular aggregates of certain green ferruginous silicates are of common occurrence among the crystals and cavities of old pyroxenic volcanic rocks. Orthoclase crystals are often mottled with patches of a granular nature, due to partial conversion of the mineral into kaolin. The magnetite, so frequently enclosed within minerals, is abundantly oxidized, and has given rise to brown and yellow patches and discolorations. Care must be taken not to confound these results of infiltrating water with the original characters of a rock. Practice will give the student confidence in distinguishing them, if he familiarises his eye with decomposition products by studying slices of weathered minerals and of the weathered parts of rocks.

B. Glass.—Even to the unassisted eye, many volcanic rocks consist obviously in whole or in great measure of glass.[4] This substance in mass is usually black or dark green, but when examined in thin sections under the microscope, it presents for the most part a pale brown tint, or is nearly colourless. In its purest condition, it is quite structureless, that is, it contains no crystals, crystallites, or other distinguishable individualised bodies. But even in this state it may sometimes be observed to be marked by clot-like patches or streaks of darker and lighter tint, arranged in lines or eddy-like curves, indicative of the flow of the original fluid mass. Rotated in the dark field of crossed Nicol-prisms, such a natural glass remains dark, as, unless where it has undergone internal stresses, it is perfectly inert in polarized light. Being thus *isotropic*, it may readily be distinguished from any enclosed crystals which, acting on the light, are *anisotropic* (p. 94). Perfectly homogeneous structureless glass, without enclosures of any kind, occurs for the most part only in limited patches, even in the most thoroughly vitreous rocks. Originally the structure of all glassy rocks, at the time of most complete fusion, may have been that of perfectly unindividualised glass. But as these masses tended towards a solid form, devitrification of their glass set in. Many forms of incipient or imperfect crystallization, as well as perfect crystals, were developed in the still fluid and moving mass, and, together with crystals of earlier growth, were arranged in the direction of motion. Devitrification has in frequent examples proceeded so far that no trace remains of any actual glass.[1]

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[1] J. A. Phillips, *Q. J. Geol. Soc.* xxxi. p. 388.

[2] Fouqué and Michel-Lévy, 'Min. Micrograph.'

[3] 'Synthèse des Minéraux,' 1882, p. 155.

[4] See E. Cohen on glassy Rocks. *Neues Jahrb.* 1880 (ii.), p. 23.

C. CRYSTALLITES AND MICROLITES.[2]—Under these names may be included minute inorganic bodies possessing a more or less definite form, but generally without the geometrical characters of crystals. They occur most commonly in rocks which have been formed from igneous fusion, but are found also in others which have resulted from, or have been altered by, aqueous solutions. They seem to be early or peculiar forms of crystallization. They are abundantly developed in artificial slags, and appear in many modern and ancient vitreous rocks, but the conditions under which they are produced are not yet well understood.[3]

Crystallites are distinguished by remaining isotropic in polarized light. The simplest are extremely minute drop-like bodies or *globulites*, sometimes crowded confusedly through the glass, giving it a dull or somewhat granular character, while in other cases they are arranged in lines or groups. Gradations can be traced from spherical or spheroidal globulites into other forms more elliptical in shape, but still having a rounded outline and sometimes sharp ends (*longulites*). There does not appear to be any essential distinction, save in degree of development, between these forms and the long rod-like or needle-shaped bodies which have been termed *belonites.* Existing sometimes as mere simple needles or rods, these more elongated crystallites may be traced into more complex forms, curved or coiled, at one time solitary, at another in groups. In most cases, crystallites are transparent and colourless, or slightly tinted, but sometimes they are black and opaque, from a coating of ferruginous oxide, or only appear so as an optical delusion from their position. Black, seemingly opaque, hair-like, twisted and curved forms, termed *trichites,* occur abundantly in obsidian.

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[1] Consult a paper on the microscopic character of devitrified glass and some analogous rock-structures, by D. Herman and F. Rutley. *Proc. Roy. Soc.* 1885, p. 87.

[2] The word *crystallite* was first used by Sir James Hall to denote the lithoid substance obtained by him after fusing and then slowly cooling various "whinstones" (diabases, &c.) Since its revival in lithology it has been applied to the minuter bodies above described. The student should consult Vogelsang's 'Philosophie der Geologie,' p. 139; 'Krystalliten,' Bonn, 8vo, 1875; also his descriptions in *Archives Néerlandaises*, v. 1870, vi. 1871. Sorby, *Brit. Assoc.* 1880.

[3] They are well exhibited also in ordinary blow-pipe beads. See Sorby, *Brit. Assoc.* 1880, or *Geol. Mag.* 1880, p. 468. They have been produced experimentally in the artificial rocks fused by Messrs. Fouqué and Michel-Lévy.

Microlites are other incipient forms of crystallization which differ from crystallites in that they react on polarized light. They assume rod-like or needle-shaped forms sometimes occurring singly, sometimes in aggregates, and even occasionally grouped into skeleton-crystals. They can for the most part be identified as rudimentary forms of definite minerals such as augite, hornblende, felspar, olivine, and magnetite.

Good illustrations of the general character and grouping of crystallites and microlites are shown in some vitreous basalts. In Fig. 13, for example, the outer portion of the field displays crowded globulites and longulites, as well as here and there a few belonites and some curved and coiled trichites. Round the rude augite crystal, these various bodies have been drawn together out of the surrounding glass. Numerous rod-like microlites diverge from the crystal, and these are more or less thickly crusted with the simpler and smaller forms.[1] In Fig. 14, the remarkably beautiful structure of an Arran pitchstone is shown; the glassy base being crowded with minute microlites of hornblende which are grouped in a fine feathery or brush-like arrangement round tapering rods. In this case, also, we see that the glassy base has been clarified round the larger individuals by the abstraction of the crowded smaller microlites.

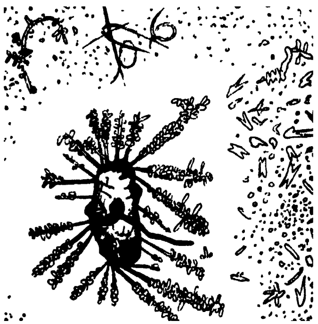

Fig. 13.—Augite Crystal surrounded by Crystallites and Microlites, from the vitreous Andesite of Eskdalemuir, magnified 800 Diameters.

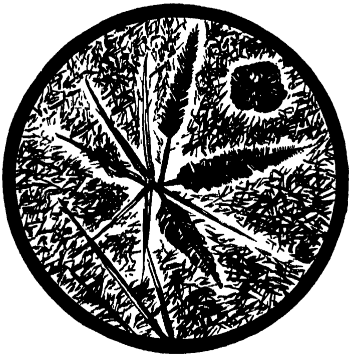

Fig. 14.—Microlites of the Pitchstone of Arran, magnified 70 Diameters. (See p. 163.)

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[1] *Proc. Roy. Phys. Soc. Edin.* v. p. 246, Plate v. Fig. 5. J. J. H. Teall, *Q. J. Geol. Soc.* xl. p. 221, Plate xii. Fig. 2a.

By the progressive development of crystallites, microlites, or crystals during the cooling and consolidation of a molten rock, a glass loses its vitreous character and becomes lithoid; in other words, undergoes devitrification.

The characteristic amorphous or indefinitely granular and fibrous or scaly matter, constituting the microscopic base in which the definite crystals of felsites and porphyries are imbedded (pp. 160, 161), has been the subject of much discussion. Between crossed Nicol-prisms it sometimes behaves isotropically, like a glass, but in other cases allows a mottled glimmering light to pass through. It is now well understood to be a product of the devitrification of once glassy rocks wherein the crystallitic and microlitic forms can still be recognised or have been more or less effaced by subsequent alteration by infiltrating water.[1]

Every gradation in the relative abundance of crystallites may be traced. In some obsidians and other vitreous rocks, portions of the glass can be obtained with comparatively few of them; but in the same rocks we may not infrequently observe adjacent parts where they have been so largely developed as to usurp the place of the original glass, and give the rock in consequence a lithoid aspect (Fig. 11, C and pp. 160-3).

D. DETRITUS.—Many rocks are composed of the detritus of pre-existing materials. In the great majority of cases this can be readily detected, even with the naked eye. But where the texture of such detrital or fragmental (clastic) rocks becomes exceedingly fine, their true nature may require elucidation with the microscope (Figs. 21, 22). An obvious distinction can be drawn between a mass of compact detritus and a crystalline or vitreous rock. The detrital materials are found to consist of various and irregularly shaped grains, with more or less of an amorphous and generally granular paste. In some cases, the grains are broken and angular, in others they are rounded or waterworn (pp. 128, 129). They may consist of minerals (quartz, chert, felspars, mica, &c.), or of rocks (slate, limestone, basalt, &c.), or of the remains of plants or animals (spores of lycopods, fragments of shells, crinoids, &c.) It is evident therefore that though some of them may be crystalline, the rock of which they now form part is a non-crystalline compound. Water, with carbonate of lime or other mineral matter in solution, permeating a detrital rock, has sometimes allowed its dissolved materials to crystallize among the interstices of the detritus, thus producing a more or less distinctly crystalline structure. But the fundamentally secondary or derivative nature of the mass is not always thereby effaced.

2. *Microscopic Structures of Rocks.*

We have next to consider the manner in which the foregoing microscopic elements are associated in rocks. This inquiry brings before us the minute structure or texture of rocks, and throws great light upon their origin and history.[2]

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[1] See Zirkel, 'Mik. Beschaff.' p. 280. Rosenbusch, vol. ii. p. 60.

[2] The first broad classification of the microscopic structure of rocks was that proposed by Zirkel, which, with slight modification, is here adopted. 'Mik. Beschaff.' p. 265.

Four types of rock-structure are revealed by the microscope. A, holocrystalline; B, hemi-crystalline; C, glassy; D, clastic.

A. HOLOCRYSTALLINE, consisting entirely of crystals or crystalline individuals, whether visible to the naked eye, or requiring the aid of a microscope, imbedded in each other without any intervening amorphous substance. Rocks of this type are exemplified by granite (Figs. 15 and 29) and by other igneous rocks. But they occur also among the crystalline limestones and schists, as in statuary marble, which consists entirely of crystalline granules of calcite (Fig. 28).

According to the classification proposed by Prof. Rosenbusch the holocrystalline structure is *idiomorphic* or *panidiomorphic* when each of the component crystals has assumed its own crystallographic form, and *allotriomorphic* when it has its outlines determined by those of its neighbours. When interspaces have been left between the crystals or crystalline grains the structure is *miarolitic* or saccharoid.

The holocrystalline eruptive rocks (p. 154) are typically represented by granite, hence the term *granitoid* has been adopted to express their microscopic structure. Varieties of this structure are designated according to the relations of the component minerals. Where no one mineral greatly preponderates, but where they are all confusedly and tolerably equally distributed in individuals readily observable by the naked eye, as ordinary granite, the structure is *granitic* (see *granular*, p. 99). Where a similar structure is so fine that it can only be recognised with the microscope, it has been called *microgranitic* or *euritic*. Where the minerals are grouped in small, isolated, grain-like individuals,

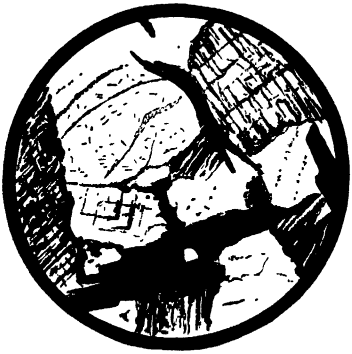

Fig. 15.—Holocrystalline Structure. Granite (20 Diameters). The white portions are Quartz, the striped parts Felspar, the long, dark, finely striated stripes are Mica. (See p. 156.)

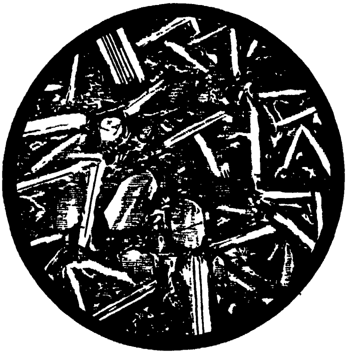

Fig. 16.—Hemi-crystalline Structure. Dolerite, consisting of a triclinic Felspar, Augite, and Magnetite in a devitrified Ground-mass (20 Diameters). The numerous narrow prisms are triclinic Felspar; the broader monoclinic forms, slightly shaded in the drawing, are Augite; the black specks are Magnetite; the needle-shaped forms are Apatite. (See p. 169.)

‘Basaltgesteine,’ p. 88. See also Rosenbusch's suggestive paper already cited, *Neues Jahrb.* 1882 (ii.), p. 1.

each having its own independent crystalline structure, so that under the microscope in polarized light, the rock presents the appearance of a brilliant mosaic, the structure has been named *granulitic* or *microgranulitic* (*panidiomorphic granular* or *porphyric* of Rosenbusch). Where the quartz and felspar of a granitic rock have crystallized together, one within the other, the structure is *pegmatitic* (Fig. 31) where visible to the naked eye, and *micropegmatitic* (*granophyric* of Rosenbusch) where the help of a microscope is needed (Fig. 5).[1]

B. HEMI-CRYSTALLINE.[2]—This division probably comprehends the majority of the massive eruptive or igneous rocks. It is distinguished by the occurrence of what appears to the naked eye as a compact or finely granular ground-mass, through which more or less recognisable crystals are scattered. Examined with the microscope, this ground-mass is found to present considerable diversity (Figs. 16, 18, 32). It may be (1) wholly a glass, as in some basalts, trachytes, and other volcanic products; (2) partly devitrified through separation of peculiar little granules and needles (crystallites and microlites) which appear in a vitreous base; (3) still further devitrified, until it becomes an aggregation of such little granules, needles, and hairs, between which little or no glass-base appears (micro-crystallitic); or (4) "microfelsitic" (petrosiliceous), closely related to the two previous groups, and consisting of a nearly structureless mass, marked usually with indefinite or half-effaced granules and filaments, but behaving like a singly-refracting, amorphous body (p. 115).

In rocks belonging to this type, a *spherulitic* structure has sometimes been produced by the appearance of globular bodies composed of a

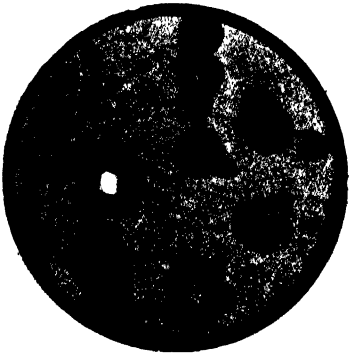

Fig. 17.—Spherulitic Structure. Pitchstone, Raasay (magnified).

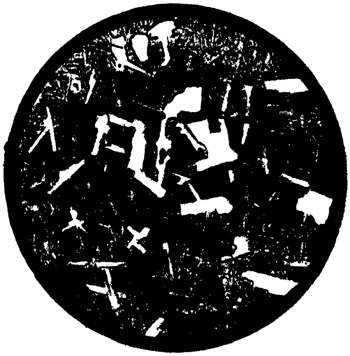

Fig. 18.—Ophitic Structure. Dolerite, Skye (magnified).

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[1] Fouqué and Michel-Lévy, 'Min. Micrograph.' The micropegmatite of Michel-Lévy is the same as the structure subsequently named granophyre by Rosenbusch. Michel Lévy, 'Roches Eruptives,' p. 19.

[2] For this structure the term "mixed" has been proposed, as being a mixture of the crystalline and amorphous (glassy) structures. It has been designated by Fouqué and Michel-Lévy "trachytoid," as being typically developed among the trachytes (*postea* p. 166). It is called "hypocrystalline" by Rosenbusch.

crystalline internally radiating substance, sometimes with concentric shells of amorphous material. In many cases, spherulites are only recognisable with the microscope, when they each present a black cross between crossed Nicol-prisms, and thereby characteristically reveal the *microspherulitic* structure (Figs. 7 and 17).[1]

The term ophitic is applied to a structure in which one mineral after crystallizing has been enclosed within another during the consolidation of an igneous rock (Fig. 18). It is abundant in many dolerites and diabases where some bisilicate such as augite serves as a matrix in which the felspars and other crystals are enclosed. The name is derived from the so-called "ophites" of the Pyrenees.[2]

C. GLASSY.—Composed of a volcanic glass such as has already been described. It seldom happens, however, that rocks which seem to the eye to be tolerably homogeneous glass do not contain abundant crystallites and minute crystals. Hence truly vitreous rocks tend to graduate into the second or hemi-crystalline type. This gradation and the abundant traces of a devitrified base or magma between the crystals of a vast number of eruptive rocks, lead to the belief that the glassy type was the original condition of most if not all of these rocks. Erupted as molten masses, their mobility would depend upon the fluidity of the glass. Yet even while still deep within the earth's crust, some of their constituent minerals (felspars, leucite, magnetite, &c.) were often already crystallized, and suffered fracture and corrosion by subsequent action of the enclosing magma. This is well shown by what is termed the *flow-structure* or *fluxion-structure*. Crystals and crystallites are ranged in current-like lines, with their long axes in the direction of these lines. Where a large older crystal occurs, the train of minuter individuals is found to sweep round

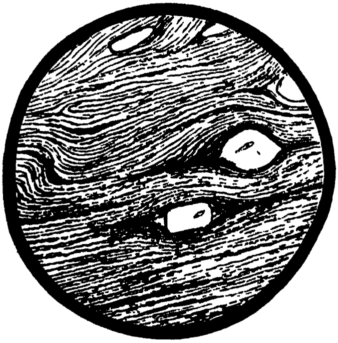

Fig. 19 —Flow-structure in Obsidian. (20 Diameters. See p. 162.)

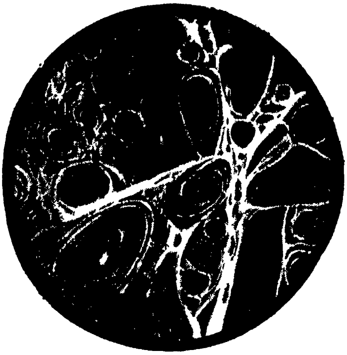

Fig. 20.—Perlitic Structure. Felsitic glass. Mull (magnified).

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[1] Fouqué and Michel-Lévy, 'Min. Micrograph.' Some remarkably beautiful examples of microspherulitic structure occur in the quartz-porphyries that traverse the lower Cambrian tuffs at St. David's. *Q. J. Geol. Soc.* xxxix. p. 313.

[2] These rocks (diabases) have been critically studied by J. Kuhn, *Zeitsch. Deutsch. Geol. Ges.* xxxiii. (1881), 372.

it and to reunite on the further side, or to be diverted in an eddy-like course (Fig. 19). So thoroughly is this arrangement characteristic of the motion of a somewhat viscid liquid, that there cannot be any doubt that such was the condition of these masses before their consolidation. The flow-structure may be detected in many eruptive rocks, from thoroughly vitreous compounds like obsidian, on the one hand, to completely crystalline masses like some dolerites, on the other. It occurs not only in what are usually regarded as volcanic rocks, but also in plutonic or deep-seated masses which, there is reason to believe, consolidated beneath the surface, as for instance in the Bode vein of the Harz, among quartz-porphyries associated with granites in Aberdeenshire, and in felsite dykes and bosses in the Shetlands, Skye, central Scotland, and County Waterford. The structure, therefore, cannot be regarded as certainly indicating that the rock in which it is found ever flowed out at the surface as lava.

Some glassy rocks, in cooling and consolidating, have had spherulites developed in them (Fig. 17); also by contraction the system of reticulated and spiral cracks known as *perlitic* structure (p. 101 and Figs. 9 and 20).

The final stiffening of a vitreous mass into solid stone has resulted (1st) from mere solidification of the glass: this is well seen at the edge of dykes and intrusive sheets of different basalt-rocks, where the igneous mass, having been suddenly congealed along its line of contact with the surrounding rocks, remains there in the condition of glass, though only an inch further inward from the edge the vitreous magma has disappeared, as represented in Fig. 287; (2nd) from the devitrification of the glass by the abundant development of microfelsitic granules and filaments, as in quartz-porphyry, or of crystallites, microlites and crystals, as in such glassy rocks as obsidian and tachylite; or (3rd) from the complete crystallization of the whole of the original glassy base, as may be observed in some dolerites.

D. CLASTIC.—Composed of detrital materials, such as have been already described (p. 103 and Fig. 21). Where these materials consist of grains of quartz-sand, they withstand almost any subsequent change, and hence can be recognised even among a highly metamorphosed series of rocks. Quartzite from such a series can sometimes be scarcely distinguished under the microscope from unaltered quartzose sandstone. Where the detritus has resulted from the destruction of aluminous or magnesian silicates, it is more susceptible of alteration. Hence it can be traced in regions of local metamorphism, becoming more and more crystalline, until the rocks formed of or containing it pass into true crystalline schists.

Detritus derived from the comminution or decay of organic remains presents very different and characteristic structures[1] (Fig. 22). Sometimes it is of a siliceous nature, as where it has been derived from diatoms and radiolarians. But most of the organically-derived detrital rocks are calcareous, formed from the remains of foraminifera, corals, echinoderms, polyzoa, cirripedes, annelides, mollusks, crustacea and other invertebrates, with occasional traces of fishes or even of higher vertebrates. Distinct differences of microscopic structure can be detected in the hard parts of some of the living representatives of these forms, and similar differences have been detected in beds of limestone of all ages. Mr. Sorby, in the paper cited below, has shown how characteristic and persistent are some of these distinctions, and how they may be made to indicate the origin of the rock in which they occur. There is an important difference between the two forms in which carbonate of lime is made use of by invertebrate animals; aragonite being much less durable than calcite (pp. 78, 139). Hence while shells of gasteropods, many lamellibranchs, corals and other organisms, formed largely or wholly of aragonite, crumble down into mere amorphous mud, pass into crystalline calcite, or disappear, the fragments of those consisting of calcite may remain quite recognisable.

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[1] The student who would further investigate this subject, will find a suggestive and luminous essay upon it by Mr. Sorby in his Presidential Address to the Geological Society. *Quart. Journ. Geol. Soc.* 1879.

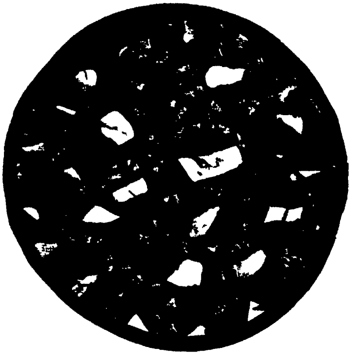

Fig. 21.—Clastic Structure, of Inorganic origin—Section of a Piece of Greywacke. (10 Diameters. See p. 132.)

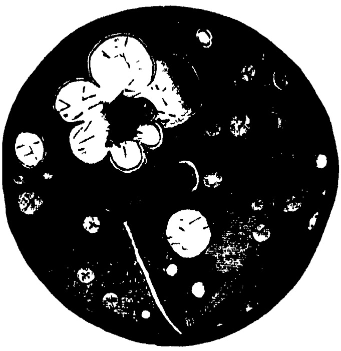

Fig. 22.—Clastic Structure, of Organic Origin—Structure of Chalk (Sorby). Magnified 100 Diameters. (See p. 140.)

It is evident, therefore, that the absence of all trace of organic structure in a limestone need not invalidate an inference from other evidence that the rock has been formed from the remains of organisms. The calcareous organic débris of a sea-bottom may be disintegrated, and reduced to amorphous detritus, by the mechanical action of waves and currents, by the solvent chemical action of the water, by the decay of the binding material, such as the organic matter of shells, or by being swallowed and digested by other animals (*postea*, p. 138).[1]

Moreover, in clastic calcareous rocks, owing to their liability to alteration by infiltrating water, there is a tendency to acquire an internal crystalline texture (p. 366). At the time of formation, little empty spaces lie between the component granules and fragments, and according to Mr. Sorby, these interspaces may amount to about a quarter of the whole mass of the rock. They have very commonly been filled up by calcite introduced in solution. This infiltrated calcite acquires a crystalline structure, like that of ordinary mineral-veins. But the original component organic granules also themselves become crystalline, and, save in so far as their external contour may reveal their original organic source, they cannot be distinguished from mere mineral-grains. In this way, a cycle of geological change is completed. The calcium-carbonate originally dissolved out of rocks by infiltrating water, and carried into the sea, is secreted from the oceanic waters by corals, foraminifera, echinoderms, mollusks and other invertebrates. The remains of these creatures collected on the sea-bottom slowly accumulate into beds of detritus, which in after times are upheaved into land. Water once more percolating through the calcareous mass, gradually imparts to it a crystalline structure, and eventually all trace of organic forms may be effaced. But at the same time, the rock, once exposed to meteoric influences, is attacked by carbonated water, its molecules are carried in solution into the sea, where they will again be built up into the framework of marine organisms.

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[1] Sorby, Presidential Address, *Q. J. Geol. Soc.* 1879. G. Rose, *Abhandl. Acad. Berlin*, 1858; Gümbel, *Zeitsch. Deutsch. Geol. Gesellsch.* 1884, p. 386. Cornish and Kendall, *Geol. Mag.* 1888, p. 66.

E. ALTERATION OF ROCKS BY METEORIC WATER.—An important revelation of the microscope is the extent to which rocks suffer from the influence of infiltrating water. The nature of some of these changes is described in subsequent pages. (Book III. Part II. Sect. ii. § 2.) It may be sufficient to note here a few of the more obvious proofs of alteration. Threads and kernels of calcite running through an eruptive rock, such as diabase, dolerite, or andesite, are a good index of internal decomposition. They usually point to the decay of some lime-bearing mineral in the rock. Some other minerals are likewise frequent signs of alteration, such as serpentine (often resulting from the alteration of olivine (Figs. 33, 34), chlorite, epidote, limonite, chalcedony, &c. In many cases, however, the decomposition products are so indefinite in form and so minute in quantity, as not to permit of their being satisfactorily referred to any known species of mineral. For these indeterminate, but frequently abundant substances, the following short names were proposed by Vogelsang to save periphrasis, until the true nature of the substance is ascertained. *Viridite*—green transparent or translucent patches, often in scaly or fibrous aggregations, of common occurrence in more or less decomposed rocks containing hornblende, augite, or olivine: probably in many cases serpentine, in others chlorite or delessite. *Ferrite*—yellowish, reddish, or brownish amorphous substances, probably consisting of peroxide of iron, either hydrous or anhydrous, but not certainly referable to any mineral, though sometimes pseudomorphous after ferruginous minerals. *Opacite*—black, opaque grains and scales of amorphous earthy matter, which may in different cases be magnetite, or some other metallic oxide, earthy silicates, graphite, &c.[1]

§ vi. Classification of Rocks.

It is evident that Lithology may be approached from two very different sides. We may, on the one hand, regard rocks chiefly as so many masses of mineral matter, presenting great variety of chemical composition and marvellous diversity of microscopic structure. Or, on the other hand, passing from the details of their chemical and mineralogical characters, we may look at them rather as the records of ancient terrestrial changes. In the former aspect, they present for consideration problems of the highest interest in inorganic chemistry and mineralogy; in the latter view, they invite attention to the great geological revolutions through which the planet has passed. It is evident, therefore, that two distinct systems of classification may be followed, the one based on chemical and mineralogical, the other on geological considerations.

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[1] Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. (1872), p. 529. Zirkel, *Geol. Expl. 40th Parallel*, vol. vi. p. 12.

From a chemical point of view, rocks may be grouped according to their composition; as Oxides, exemplified by formations of quartz, hæmatite, or magnetite; Carbonates, including the limestones and clay-ironstones; Silicates, embracing the vast majority of rocks, whether composed of a single mineral, or of more than one; Phosphates, such as guano and the older bone-beds and coprolitic deposits. A classification of this kind, however, pays no regard to the mode of origin or conditions of occurrence of the rocks, and is not well suited for the purposes of the geologist.[1]

From the mineralogical side, rocks may be classified with reference to their prevailing mineral constituent. Thus such subdivisions as Calcareous rocks, Quartzose rocks, Orthoclase rocks, Plagioclase rocks, Pyroxenic rocks, Hornblendic rocks, &c., may be adopted; but these terms are hardly less objectionable to the geologist, and are in fact suited rather for the arrangement of hand-specimens in a museum, than for the investigation of rocks *in situ*.

From the standpoint of geological inquiry, rocks have been classified according to their mode of origin. In one system they are arranged under three great divisions: 1st, *Igneous*, embracing all which have been erupted from the heated interior of the earth; 2nd, *Aqueous* or *Sedimentary*, including all which have been laid down as mechanical or chemical deposits from water or air, and all which have resulted from the growth and decay of plants or animals; 3rd, *Metamorphic*, those which have undergone subsequent change within the crust of the earth, whereby their original character has been so modified as to be sometimes quite indeterminable. Another geological arrangement is based upon the general structure of the rocks, and consists of two divisions, 1st, *Stratified*, embracing all the aqueous and sedimentary, with part of the less altered metamorphic rocks; 2nd, *Unstratified*, nearly conterminous with the term igneous, since it includes all the eruptive rocks. Further subdivisions of this series have been proposed according to differences of structure or texture, as *porphyritic*, *granitic*, &c. These geological subdivisions, however, ignore the chemical and mineralogical characters of the rocks, and are based on deductions which may not always be sound. Thus, rocks may be included in the igneous series, which further research may show not to be of igneous origin; others may be classed as metamorphic, regarding the true origin of which there may be considerable uncertainty.

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[1] The eruptive rocks are susceptible of a convenient, though not strictly accurate, chemical classification into *acid*, *intermediate*, and *basic* (see p. 156).

A further system of classification, based upon relative age, has been applied to the arrangement of the eruptive rocks, those masses which were erupted prior to Secondary time being classed as "older," and those of Tertiary and later date as "younger." This system has been elaborated in great detail by Michel-Lévy, who maintains that the same types have been reproduced nearly in the same order in the two series, though basic rocks, often with vitreous characters, rather predominate in the later.[1] It must, indeed, be admitted that certain broad distinctions between the older and the later eruptive rocks have been well ascertained, and appear to hold generally over the world. Among these distinctions may be mentioned as more characteristic of the Palæozoic rocks the presence of microcline, turbid orthoclase in Carlsbad twins, muscovite, enstatite, bronzite, diallage, tourmaline, anatase, rutile, cordierite, and in the younger rocks the presence of sanidine, tridymite, leucite, nosean, hauyne, and zeolites. Even where the same mineral occurs in both the older and newer series, it often presents a somewhat different aspect in each, as in the case of the plagioclase and augite, which in the younger series are distinguished by the occurrence in them of vitreous and gaseous inclusions which are rare or absent in those of the older series.[2] Throughout the younger eruptive rocks, the vitreous condition is much more frequent and perfectly developed than in the older group, where, on the other hand, the granitic structure is characteristically displayed. Still, to these rules so many exceptions occur that it may be doubted whether enough of positively ascertained data have been collected regarding the relative ages of eruptive rocks to warrant the adoption of any classification upon a chronological basis. There can be no doubt that, making due allowance for the alterations arising from permeation by meteoric water, there is no essential difference between some types of volcanic rock in Palæozoic and in recent times. The Carboniferous basalts and trachytes of Scotland, for example, present the closest resemblance to those of Tertiary age.[3]

Though no classification which can at present be proposed is wholly satisfactory, one which shall do least violence, at once to geological and mineralogical relationships, is to be preferred. The arrangement which has met with the most general acceptance is threefold. 1st, Sedimentary Rocks, including first the rocks which have resulted from the accumulation of detritus, either inorganic or organic, under water or on land, and secondly those which have been deposited from aqueous solution. The former are mechanical, the latter chemical accumulations; but they have often been deposited together. Certain rocks of mechanical origin, such as detrital limestones, may by subsequent alteration be converted into materials that cannot be distinguished from others of true chemical origin. Hence the whole series is intimately linked together. 2nd, Massive, Eruptive, or Intrusive Rocks, embracing all those which have solidified from fusion within the earth's crust, or have been erupted as lava to the surface. 3rd, Schistose Rocks, and their accompaniments, including the so-called Metamorphic rocks which have reached their present condition as a consequence of the alteration sometimes of sedimentary, sometimes of igneous rocks. This group graduates into the two others, but it contains some distinctive masses, the origin of which is still involved in doubt.

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[1] See on this subject, J. D. Dana, *Amer. J. Sci.* xvi. 1878, p. 336. Michel-Lévy, *Bull. Soc. Géol. France*, 3rd ser. iii. (1874), p. 199; vi. p. 173. *Ann. des Mines*, viii. (1875) 'Roches Eruptives,' 1889. Fouqué and Michel-Lévy, 'Minéralogie Microgr.' p. 150. Rosenbusch, 'Mik. Physiog.' ii. Reyer, 'Physik der Eruptionen,' 1877, part iii. opposes the adoption of relative age as a basis of classification. On the classification of compound silicated rocks, see Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. p. 507; and for an incisive criticism of a too merely mineralogical classification, Lossen, *op. cit.* xxiv. p. 782. Consult also O. Lang, 'Über die Individualität der Gesteine' in *Tschermak's Min. Mittheil.* vol. xi. part 6 (1890), p. 467.

[2] See J. Murray and A. Renard, *Proc. Roy. Soc. Edin.* xi. p. 669.

[3] See *Nature*, iii. (1871), p. 303.

It must be kept in view that in this proposed system of classification, and in the following detailed description of rocks, many questions regarding the origin and decomposition of these mineral masses must necessarily be alluded to. The student, however, will find these questions discussed in later pages, and will probably recognise a distinct advantage in this unavoidable preliminary reference to them in connection with the rocks by which they are suggested.

§ vii.—A Description of the more Important Rocks of the Earth's Crust.

Full details regarding the composition, microscopic structure, and other characters of rocks must be sought in such general treatises and special memoirs as those already cited (pp. 89, 96, 108). The purposes of the present text-book will be served by a succinct account of the more common or important rocks which enter into the composition of the crust of the earth.

I. SEDIMENTARY.

A. FRAGMENTAL (CLASTIC).

This great series embraces all rocks of a secondary or derivative origin; in other words, all formed of fragmentary materials which have previously existed on or beneath the surface of the earth in another form, and the accumulation and consolidation of which gives rise to new compounds. Some of these materials have been produced by the mechanical action of wind, as in the sand-hills of sea-coasts and inland deserts (Æolian rocks); others by the operation of moving water, as the gravel, sand and mud of shores and river-beds (Aqueous sedimentary rocks); others by the accumulation of the entire or fragmentary remains of once living plants and animals (Organically-formed rocks); while yet another series has arisen from the gathering together of the loose débris thrown out by volcanoes (Volcanic tuffs). It is evident that in dealing with these various detrital formations, the degree of consolidation is of secondary importance. The soft sand and mud of a modern lake-bottom differ in no essential respect from ancient lacustrine strata, and may tell their geological story equally well. No line is to be drawn between what is popularly termed rock and the loose, as yet uncompacted, débris out of which solid rocks may eventually be formed. Hence in the following arrangement, the modern and the ancient, being one in structure and mode of formation, are classed together.

It will be observed that, in several directions, we are led by the fragmental rocks to crystalline stratified deposits, some of which have been deposited from chemical solution, while others have resulted from the gradual conversion of a detrital into a crystalline structure. Both series of deposits are accumulated simultaneously and are often interstratified. Calcareous rocks formed of organic remains (p. 138) exhibit very clearly this gradual internal change, which more or less effaces their detrital origin, and gives them such a crystalline character as to entitle them to be ranked among the crystalline limestones.

1. **Gravel and Sand Rocks** (Psammites).

As the deposits included in this subdivision are produced by the disintegration and removal of rocks by the action of the atmosphere, rain, rivers, frost, the sea, and other superficial agencies, they are mere mechanical accumulations, and necessarily vary indefinitely in composition, according to the nature of the sources from which they are derived. As a rule, they consist of the detritus of siliceous rocks, these being among the most durable materials. Quartz, in particular, enters largely into the composition of sandy and gravelly detritus. Fragmentary materials tend to group themselves according to their size and relative density. Hence they are apt to occur in layers, and to show the characteristic *stratified* arrangement of *sedimentary* rocks. They may enclose the remains of any plants or animals entombed on the same sea-floor, river-bed, or lake-bottom.

In the majority of these rocks, their general mineral composition is obvious to the naked eye. But the application of the microscope to their investigation has thrown considerable light upon their composition, formation, and subsequent mutations. Their component materials are thus ascertained to be divisible into—1st, derived fragments, of which the most abundant are quartz, after which come felspar, mica, iron-ores, zircon, rutile, apatite, tourmaline, garnet, sphene, augite, hornblende, fragments of various rocks, and clastic dust; 2nd, constituents which have been deposited between the particles, and which in many cases serve as the cementing material of the rock. Among the more important of these are silicic acid in the form of quartz, chalcedony and opal; carbonates of lime, iron or magnesia; hæmatite, limonite; pyrite and glauconite.[1]

Cliff-Débris, Moraine Stuff—angular rubbish disengaged by frost and ordinary atmospheric waste from cliffs, crags, and steep slopes. It slides down the declivities of hilly regions, and accumulates at their base, until washed away by rain or by brooks. It forms talus-slopes of as much as 40°, though for short distances, if the blocks are large, the general angle of slope may be much steeper. It naturally depends for its composition upon the nature of the solid rocks from which it is derived. Where cliff-débris falls upon and is borne along by glaciers it is called "Moraine-stuff," which may be deposited near its source, or may be transported for many miles on the surface of the ice (p. 423).

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[1] G. Klemm, *Zeitsch. Deutsch. Geol. Ges.* xxxiv. (1882), p. 771. H. C. Sorby, *Quart. Journ. Geol. Soc.* xxxvi. (1880). J. A. Phillips, *op. cit.* xxxvii. (1881), p. 6.

Perched Blocks, Erratic Blocks—large masses of rock, often as big as a house, which have been transported by glacier-ice, and have been lodged in a prominent position in glacier valleys or have been scattered over hills and plains. An examination of their mineralogical character leads to the identification of their source and, consequently, to the path taken by the transporting ice. (See Book III. Part II. Section ii. § 5.)

Rain-wash—a loam or earth which accumulates on the lower parts of slopes or at their base, and is due to the gradual descent of the finer particles of disintegrated rocks by the transporting action of rain. Brick-earth is the name given in the south-east of England to thick masses of such loam, which is extensively used for making bricks.

Soil—the product of the subaerial decomposition of rocks and of the decay of plants and animals. Primarily the character of the soil is determined by that of the subsoil, of which indeed it is merely a further disintegration. According to the nature of the rock underneath, a soil may vary from a stiff clay, through various clayey and sandy loams, to mere sand. The formation of soil is treated of in Book III. Part II. Section ii. § i.

Subsoil—the broken-up part of the rocks immediately under the soil. Its character, of course, is determined by that of the rock out of which it is formed by subaerial disintegration. (Book III. Part II. Section ii. § 1.)

Blown Sand—loose sand usually arranged in lines of dunes, fronting a sandy beach or in the arid interior of a continent. It is piled up by the driving action of wind. (Book III. Part II. Section i.) It varies in composition, being sometimes entirely siliceous, as upon shores where siliceous rocks are exposed; sometimes calcareous, where derived from triturated shells, nullipores, or other calcareous organisms. The minute grains from long-continued mutual friction assume remarkably rounded and polished forms. Layers of finer and coarser particles often alternate, as in water-formed sandstone. On many coast-lines in Europe, grasses and other plants bind the surface of the shifting sand. These layers of vegetation are apt to be covered by fresh encroachments of the loose material, and then by their decay to give rise to dark peaty seams in the sand. Calcareous blown sand is compacted into hard stone by the action of rain-water, which alternately dissolves a little of the lime, and re-deposits it on evaporation as a thin crust cementing the grains of sand together. In the Bahamas and Bermudas, extensive masses of calcareous blown sand have been cemented in this way into solid stone, which weathers into picturesque crags and caves like a limestone of older geological date.[1] At Newquay, Cornwall, blown sand has been by the decay of abundant land-shells solidified into a material capable of being used as a building-stone.

River-sand, Sea-sand.—When the rounded water-worn detritus is finer than that to which the term gravel would be applied, it is called sand, though there is obviously no line to be drawn between the two kinds of deposit, which necessarily graduate into each other. The particles of sand range down to such minute forms as can only be distinctly discerned with a microscope. The smaller forms are generally less well rounded than those of greater dimensions, no doubt because their diminutive size allows them to remain suspended in agitated water, and thus to escape the mutual attrition to which the larger and heavier grains are exposed upon the bottom. (Book III. Part II. Section ii.) So far as experience has yet gone, there is no method by which inorganic sea-sand can be distinguished from that of rivers or lakes. As a rule, sand consists largely

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[1] For interesting accounts of the Æolian deposits of the Bahamas and Bermudas, see Nelson, *Q. J. Geol. Soc.* ix. p. 200, Sir Wyville Thomson's "Atlantic," vol. i.; also J. J. Rein, *Senckenb. Nat. Gesellsch. Bericht.* 1869-70, p. 140, 1872-3, p. 131. On the Red Sands of the Arabian Desert, see J. A. Phillips, *Q. J. Geol. Soc.* xxxviii. (1882), p. 110, also *op. cit.* xxxvii. (1881), p. 12.

(often wholly) of quartz-grains. The presence of fragments of marine shells will of course betray its salt-water origin; but in the trituration to which sand is exposed on a coast-line, the shell-fragments are in great measure ground into calcareous mud and removed.

Mr. Sorby has shown that, by microscopic investigation, much information may be obtained regarding the history and source of sedimentary materials. He has studied the minute structure of modern sand, and finds that sand-grains present the following five distinct types, which, however, graduate into each other.

1. Normal, angular, fresh-formed sand, such as has been derived almost directly from the breaking up of granitic or schistose rocks.
2. Well-worn sand in rounded grains, the original angles being completely lost, and the surfaces looking like fine ground glass.
3. Sand mechanically broken into sharp angular chips, showing a glassy fracture.
4. Sand having the grains chemically corroded, so as to produce a peculiar texture of the surface, differing from that of worn grains or crystals.
5. Sand in which the grains have a perfectly crystalline outline, in some cases undoubtedly due to the deposition of quartz upon rounded or angular nuclei of ordinary non-crystalline sand.[1]

The same acute observer points out that, as in the familiar case of conglomerate pebbles, which have sometimes been used over again in conglomerates of very different ages, so with the much more minute grains of sand, we must distinguish between the age of the grains and the age of the deposit formed of them. An ancient sandstone may consist of grains that had hardly been worn before they were finally brought to rest, while the sand of a modern beach may have been ground down by the waves of many successive geological periods.

Sand taken by Mr. Sorby from the old gravel terraces of the River Tay, was found to be almost wholly angular, indicating how little wear and tear there may be among particles of quartz $\frac{1}{100}$ of an inch in diameter, even though exposed to the drifting action of a rapid river.[2] Sand from the boulder clay at Scarborough was likewise ascertained to be almost entirely fresh and angular. On the other hand, in geological formations, which can be traced in a given direction for several hundred miles, a progressively large proportion of rounded particles may be detected in the sandy beds, as Mr. Sorby has found in following the Greensand from Devonshire to Kent. In wind-blown sand exposed for a long period to drift to and fro along the surface the larger particles and pebbles acquire a remarkably smoothed and polished surface.

The occurrence of various other minerals besides quartz in ordinary sand has long been recognised, but we owe to the recent observations of Mr. A. B. Dick the discovery that among these minerals some of the most plentiful and most perfectly preserved belong to species that were not supposed to be so widely diffused, such as zircon, rutile, and tourmaline. He has found that these heavy minerals constitute sometimes as much as 4 per cent of the Bagshot sand of the older Tertiary series of the London basin.[3] Felspars, micas, hornblendes, pyroxenes, magnetite, glauconite and other minerals may likewise be recognised. The remarkable perfection of some of the crystallographic forms of the minuter mineral constituents of certain sands has been well shown by Mr. Dick.

Varieties of river or sea-sand may be distinguished by names referring to some remarkable constituent, *e.g.*, magnetic sand, iron-sand, gold-sand, auriferous sand, &c.

Gravel, Shingle—names applied to the coarser kinds of rounded water-worn detritus.

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[1] Address, *Q. J. Geol. Soc.* xxxvi. (1880), p. 58, and *Monthly Microscop. Journ.* Anniv. Address, 1877.

[2] See Book III. Part II. Section ii. § iii.

[3] *Nature*, xxxvi. (1887), p. 91, *Mem. Geol. Surv.* 'Geology of London,' vol. i. (1889), p. 523. Teall, 'Microscopic Petrography,' Plate xliv.

In Gravel, the average size of the component pebbles ranges from that of a small pea up to about that of a walnut, though of course many included fragments will be observed which exceed these limits. In Shingle, the stones are coarser, ranging up to blocks as big as a man's head or larger. German geologists distinguish as "schotter," a shingle containing dispersed boulders, and "schotter-conglomerate," a rock wherein these materials have become consolidated.[1] All these names are applied quite irrespective of the composition of the fragments, which varies greatly from point to point. As a rule, the stones consist of hard rocks, since these are best fitted to withstand the powerful grinding action to which they are exposed.

Conglomerate (Puddingstone)—a rock formed of consolidated gravel or shingle. The component pebbles are rounded and water-worn. They may consist of any kind of rock, though usually of some hard and durable sort, such as quartz or quartzite. A special name may be given according to the nature of the pebbles, as quartz-conglomerate, limestone-conglomerate, granite-conglomerate, &c., or according to that of the paste or cementing matrix, which may consist of a hardened sand or clay, and may be siliceous, calcareous, argillaceous, or ferruginous. In the coarser conglomerates, where the blocks may exceed six feet in length, there is often very little indication of stratification. Except where the flatter stones show by their general parallelism the rude lines of deposit, it may be only when the mass of conglomerate is taken as a whole, in its relation to the rocks below and above it, that its claim to be considered a bedded rock will be conceded. The occurrence of occasional bands of conglomerate in a series of arenaceous strata is analogous probably to that of a shingle-bank or gravel-beach on a modern coast-line. But it is not easy to understand the circumstances under which some ancient conglomerates accumulated, such as that of the Old Red Sandstone of Central Scotland, which attains a thickness of many thousand feet, and consists of well-rounded and smoothed blocks often several feet in diameter.

In many old conglomerates (and even in those of Miocene age in Switzerland) the component pebbles may be observed to have indented each other. In such cases also they may be found elongated, distorted or split and recemented; sometimes the same pebble has been crushed into a number of pieces, which are held together by a retaining cement. These phenomena point to great pressure, and some internal relative movement in the rocks. (Book III. Part I. Section iv. § 3.)

Breccia—a rock composed of angular, instead of rounded, fragments. It commonly presents less trace of stratification than conglomerate. Intermediate stages between these two rocks, where the stones are partly angular and partly subangular and rounded, are known as *brecciated conglomerate.* Considered as a detrital deposit formed by superficial waste, breccia points to the disintegration of rocks by the atmosphere, and the accumulation of their fragments with little or no intervention of running water. Thus it may be formed at the base of a cliff, either subaerially, or where the débris of the cliff falls at once into a lake or into deep sea-water.

The term Breccia has, however, been applied to rocks formed in a totally different manner. Angular blocks of all sizes and shapes have been discharged from volcanic orifices, and, falling back, have consolidated there into masses of brecciated material (volcanic breccia). Intrusive igneous eruptions have sometimes torn off fragments of the rocks through which they have ascended, and these angular fragments have been enclosed in the liquid or pasty mass. Or the intrusive rock has cooled and solidified externally while still mobile within, and in its ascent has caught up and involved some of these consolidated parts of its own substance. Again, where solid masses of rock within the crust of the earth have ground against each other, as in dislocations, angular fragmentary rubbish has been produced, which has subsequently been consolidated by some infiltrating cement (Fault-rock). It is evident, however, that breccia formed in one or other of these hypogene ways will not, as a rule, be apt to be mistaken for the true breccias, arising from superficial disintegration.

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[1] See, for example, an account of the schotter-conglomerates of Northern Persia by E. Tietze, *Jahrb. Geol. Reichsanst.* Vienna, 1881, p. 68.

Sandstone (Grès)[1]—a rock composed of consolidated sand. As in ordinary modern sand, the integral grains of sandstone are chiefly quartz, which must here be regarded as the residue left after all the less durable minerals of the original rocks have been carried away in solution or in suspension as fine mud. The colours of sandstones arise, not so much from that of the quartz, which is commonly white or grey, as from the film or crust which often coats the grains and holds them together as a cement. Iron, the great colouring ingredient of rocks, gives rise to red, brown, yellow, and green hues, according to its degree of oxidation and hydration.

Like conglomerates, sandstones differ in the nature of their component grains, and in that of the cementing matrix. Though consisting for the most part of siliceous grains, they include others of clay, felspar, mica, zircon, rutile, tourmaline, or other minerals such as occur in sand (p. 129), and these may increase in number so as to give a special character to the rock. Thus, sandstones may be argillaceous, felspathic, micaceous, calcareous, &c. By an increase in the argillaceous constituents, a sandstone may pass into one of the clay-rocks, just as modern sand on the sea-floor shades imperceptibly into mud. On the other hand, by an augmentation in the size and sharpness of the grains, a sandstone may become a grit, and by an increase in the size and number of pebbles, may pass into a pebbly or conglomeratic sandstone, and thence into a fine conglomerate. A piece of fine-grained sandstone, seen under the microscope, looks like a coarse conglomerate, so that the difference between the two rocks is little more than one of relative size of particles.

The cementing material of sandstones may be *ferruginous*, as in most ordinary red and yellow sandstones, where the anhydrous or hydrous iron-oxide is mixed with clay or other impurity—in red sandstones the grains are held together by a hæmatitic, in yellow sandstones by a limonitic cement; *argillaceous*, where the grains are united by a base of clay, recognisable by the earthy smell when breathed upon; *calcareous*, where carbonate of lime occurs either as an amorphous paste or as a crystalline cement between the grains; *siliceous*, where the component particles are bound together by silica, as in the exposed blocks of Eocene sandstone known as "greyweathers" in Wiltshire, and which occur also over the north of France towards the Ardennes.

Among the varieties of sandstone the following may here be mentioned. Flagstone—a thin-bedded sandstone, capable of being split along the lines of stratification into thin beds or flags; Micaceous sandstone (*mica-psammite*)—a rock so full of mica-flakes that it splits readily into thin laminæ, each of which has a lustrous surface from the quantity of silvery mica. This rock is called "fakes" in Scotland. Freestone—a sandstone (the term being applied sometimes also to limestone) which can be cut into blocks in any direction, without a marked tendency to split in any one plane more than in another. Though this rock occurs in beds, each bed is not divided into laminæ, and it is the absence of this minor stratification which makes the stone so useful for architectural purposes (Craigleith and other sandstones at Edinburgh, some of which contain 98 per cent of silica). Glauconitic sandstone (green-sand)—a sandstone containing kernels and dusty grains of glauconite, which imparts a general greenish hue to the rock. The glauconite has probably been deposited in association with decaying organic matter, as where it fills echinus-spines, foraminifera, shells and corals on the floor of the present ocean.[2] Buhrstone—a highly siliceous, exceedingly compact, though cellular rock (with *Chara* seeds, &c.), found alternating with unaltered Tertiary strata in the Paris basin, and forming from its hardness and roughness, an excellent material for the grindstones of flour-mills, may be mentioned here, though it probably has been formed by the precipitation of silica through the action of organisms. Arkose (*granitic sandstone*)—a rock composed of disintegrated granite, and found in geological formations of different ages, which have been derived from granitic rocks. Crystallized sandstone—an arenaceous rock in which a deposit of crystalline quartz has taken place upon the individual grains, each of which becomes the nucleus of a more or less perfect quartz crystal. Mr. Sorby has observed such crystallized sand in deposits of various ages from the Oolites down to the Old Red Sandstone.[1]

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[1] See J. A. Phillips on the constitution and history of grits and sandstones. *Quart. Journ. Geol. Soc.* xxxvii. (1881), p. 6. For analyses of some British sandstones used as building stones, see Wallace, *Proc. Phil. Soc. Glasgow*, xiv. (1883), p. 22.

[2] *Ante*, p. 77; Sollas, *Geol. Mag.* iii. 2nd ser. p. 539.

Greywacke—a compact aggregate of rounded or subangular grains of quartz, felspar, slate, or other minerals or rocks, cemented by a paste which is usually siliceous, but may be argillaceous, felspathic, calcareous, or anthracitic (Fig. 21). Grey, as its name denotes, is the prevailing colour: but it passes into brown, brownish-purple, and sometimes, where anthracite predominates, into black. The rock is distinguished from ordinary sandstone by its darker hue, its hardness, the variety of its component grains, and, above all, by the compact cement in which the grains are imbedded. In many varieties, so pervaded is the rock by the siliceous paste, that it possesses great toughness, and its grains seem to graduate into each other as well as into the surrounding matrix. Such rocks when fine-grained, can hardly, at first sight or with the unaided eye, be distinguished from some compact igneous rocks, though a microscopic examination at once reveals their fragmental character. In other cases, where the greywacke has been formed mainly out of the débris of granite, quartz-porphyry, or other felspathic masses, the grains consist so largely of felspar, and the paste also is so felspathic, that the rock might be mistaken for some close-grained granular porphyry. Greywacke occurs extensively among the Palæozoic formations, in beds alternating with shales and conglomerates. It represents the muddy sand of some of the Palæozoic sea-floors, retaining often its ripple-marks and sun-cracks. The metamorphism it has undergone has generally not been great, and for the most part is limited to induration, partly by pressure and partly by permeation of a siliceous cement. But where felspathic ingredients prevail, the rock has offered facilities for alteration, and has been here and there changed into highly crystalline mica-schists full of garnets and other secondary minerals (contact-metamorphism at the granite of New Galloway, Scotland, *postea*, p. 606).

The more fissile fine-grained varieties of this rock have been termed greywacke-slate (p. 135). In these, as well as in greywacke, organic remains occur among the Silurian and Devonian formations. Sometimes in the Lower Silurian rocks of Scotland, these strata become black with carbonaceous matter, among which vast numbers of graptolites may be observed. Gradations into sandstone are termed Greywacke-sandstone. In Norway the reddish felspathic greywacke or sandstone of the Primordial rocks, is called Sparagmite; similar material forms much of the Torridon sandstone of Scotland.

Quartzite.—An altered siliceous sandstone (see p. 180).

2. Clay Rocks (Pelites).

These are composed of fine argillaceous sediment or mud, derived from the waste of rocks. Perfectly pure clay or kaolin, hydrated silicate of alumina, may be obtained where granites and other felspar-bearing rocks decompose. But, as a rule, the argillaceous materials are mixed with various impurities.

Clay, Mud.—The decomposition of felspars and allied minerals gives rise to the formation of hydrous aluminous silicates, which occurring usually in a state of fine subdivision, are capable of being held in suspension in water, and of being transported to great distances. These substances, differing much in composition, are embraced under the general term Clay, which may be defined as a white, grey, brown, red, or bluish substance, which when dry is soft and friable, adheres to the tongue, and shaken in water makes it mechanically turbid; when moist is plastic, when mixed with much water becomes mud. It is evident that a wide range is possible for varieties of this substance. The following are the more important.

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[1] *Q. J. Geol. Soc.* xxxvi. p. 63. See Daubrée, *Ann. des Mines*, 2nd ser. i. p. 206. A. A. Young, *Amer. Journ. Sci.* 3rd ser. xxiii. 257; xxiv. 47, and especially the work of Irving and Van Hise (quoted on p. 110), which gives some excellent figures of enlarged quartz-grains.

Kaolin (Porcelain-clay, China-clay) has been already noticed (p. 77).

Pipe-Clay—white, nearly pure, and free from iron.

Fire-Clay—largely found in connection with coal-seams, contains little iron, and is nearly free from lime and alkalies. Some of the most typical fire-clays are those long used at Stourbridge, Worcestershire, for the manufacture of pottery. The best glass-house pot-clay, that is, the most refractory, and therefore used for the construction of pots which have to stand the intense heat of a glass-house, has the following composition: silica, 73·82; alumina, 15·88; protoxide of iron, 2·95; lime, trace; magnesia, trace; alkalies, ·90; sulphuric acid, trace; chlorine, trace; water, 6·45; specific gravity, 2·51.

Gannister—a very siliceous close-grained variety, found in the Lower Coal measures of the North of England, and now largely ground down as a material for the hearths of iron furnaces.

Brick-clay—properly rather an industrial than a geological term, since it is applied to any clay, loam, or earth, from which bricks or coarse pottery are made. It is an impure clay, containing a good deal of iron, with other ingredients. An analysis gave the following composition of a brick-clay: silica, 49·44; alumina, 34·26; sesquioxide of iron, 7·74; lime, 1·48, magnesia, 5·14; water, 1·94.

Fuller's Earth (Terre à foulon, Walkerde)—a greenish or brownish, earthy, soft, somewhat unctuous substance, with a shining streak, which does not become plastic with water, but crumbles down into mud. It is a hydrous aluminous silicate with some magnesia, iron-oxide and soda. The yellow fuller's earth of Reigate contains silica 44, alumina 11, oxide of iron 10, magnesia 2, lime 5, soda 5.[1] In England fuller's earth occurs in beds among the Jurassic and Cretaceous formations. In Saxony it is found as a result of the decomposition of diabase and gabbro.

Wacke—a dirty-green to brownish-black, earthy or compact, but tender and apparently homogeneous clay, which arises as the ultimate stage of the decomposition of basalt-rocks *in situ*.

Loam—an earthy mixture of clay and sand with more or less organic matter. The black soils of Russia, India, &c. (Tchernosem, Regur), are dark deposits of loam rich in organic matter, and sometimes upwards of twenty feet deep.

Loess—a pale, somewhat calcareous clay, probably of wind-drift origin, found in some river-valleys (Rhine, Danube, Mississippi, &c.), and over wide regions in China and elsewhere. It is described in Book III. Part II. Sect. i. § 1.

Laterite—a cellular, reddish, ferruginous clay, found in some tropical countries as the result of the subaerial decomposition of rocks; it acquires great hardness after being quarried out and dried.

Till, Boulder-clay—a stiff sandy and stony clay, varying in colour and composition, according to the character of the rocks of the district in which it lies. It is full of worn stones of all sizes, up to blocks weighing several tons, and often well-smoothed and striated. It is a glacial deposit, and will be described among the formations of the Glacial Period.

Mudstone—a fine, usually more or less sandy, argillaceous rock, having no fissile character, and of somewhat greater hardness than any form of clay. The term Clay-rock has been applied by some writers to an indurated clay requiring to be ground and mixed with water before it acquires plasticity.

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[1] Ure's *Dict. Arts*, &c. ii. p. 142.

Shale (Schiste, Schieferthon)—a general term to describe clay that has assumed a thinly stratified or fissile structure. Under this term are included laminated and somewhat hardened argillaceous rocks, which are capable of being split along the lines of deposit into thin leaves. They present almost endless varieties of texture and composition, passing, on the one hand, into clays, or, where much indurated, into slates and argillaceous schists, on the other, into flagstones and sandstones, or again, through calcareous gradations into limestone, or through ferruginous varieties into clay-ironstone, and through bituminous kinds into coal.

Clay-slate (Schiste ardoise, Thonschiefer).—Under this name are included certain hard fissile argillaceous masses, composed primarily of compact clay, sometimes with megascopic and microscopic scales of one or more micaceous minerals, granules of quartz and cubes or concretions of pyrites, as well as veins of quartz and calcite. The fissile structure is specially characteristic. In some cases this structure coincides with that of original deposit, as is proved by the alternation of fissile beds with bands of hardened sandstone, conglomerate or fossiliferous limestone. But for the most part as the rocks have been much compressed, the fissile structure of the argillaceous bands is independent of stratification, and can be seen traversing it. Sorby has shown that this superinduced fissility or "cleavage" has resulted from an internal rearrangement of the particles in planes perpendicular to the direction in which the rocks have been compressed (see Book III. Part I. Section iv. § 3). In England the term "slate" or "clay-slate" is given to argillaceous, not obviously crystalline rocks possessing this cleavage-structure. Where the micaceous lustre of the finely disseminated superinduced mica is prominent, the rocks are phyllites.

Microscopic examination shows that while some argillaceous rocks consist mainly of granular débris, many cleaved clay-slates contain a large proportion of a micaceous mineral in extremely minute flakes, which in the best Welsh slates have an average size of $\frac{1}{2000}$ of an inch in breadth, and $\frac{1}{8000}$ of an inch in thickness, together with very fine black hairs which may be magnetite.[1] Moreover, many clay-slates, though to outward appearance thoroughly noncrystalline, and evidently of fragmental composition and sedimentary origin, yet contain, sometimes in remarkable abundance, microscopic microlites and crystals of different minerals placed with their long axes parallel with the planes of fissility. These minute bodies include yellowish-brown needles of rutile, greenish or yellowish flakes of mica, scales of calcite, and probably other minerals.[2] Small granules of quartz containing fluid-cavities, show on their surfaces a distinct blending with the substance of the surrounding rock. M. Renard has found that the Belgian whet-slate is full of minute crystals of garnet.[3] Some of the more crystalline varieties (phyllite) are almost wholly composed of minute crystalline particles of mica, quartz, felspar, chlorite, and rutile, and form an intermediate stage between ordinary clay-slate and mica-schist.

A distinction has been drawn by some petrographers between certain rocks (phyllite, Urthonschiefer) which occur in Archaean regions or in groups probably of high antiquity, and others (ardoise, Thonschiefer) which are found in Palæozoic and later formations. But there does not appear to be adequate justification for this grouping, which has probably been suggested rather by theoretical exigences than by any essential differences between the rocks themselves. That the whole of the series of argillaceous rocks, beginning with clay and passing through shale into slate and phyllite, is of sedimentary origin is indicated by the organic remains, false bedding, ripple-mark, &c., found in those at one end of the series, and by the insensible gradation of the mineralogical characters through increasing stages of metamorphism to the other end. Some microscopic crystals may possibly have been originally formed among the muddy sediment on the sea-floor (see p. 459). Others may have formed part of the original mechanical detritus that went to make the slate. But, for the most part, they have been subsequently developed within the rock, and represent early stages of the process which has culminated in the production of crystalline schists. The development of crystals of chiastolite and other minerals in clay-slate is frequently to be observed round bosses of granite, as one of the phases of contact-metamorphism (see pp. 568, 605).

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[1] Sorby, *Q. J. Geol. Soc.* xxvi. p. 68.

[2] These "clay-slate needles" were probably not crystallized contemporaneously with the deposit of the original rock. In some cases they may have been deposited with the rest of the sediment as part of the débris of pre-existing crystalline rocks (see p. 129); but in general they appear to have been developed where they now occur by subsequent actions (see *postea*, pp. 312, 545). For their character see Zirkel, 'Mik. Beschaff.' p. 490. Kalkowsky, *N. Jahrb.* 1879, p. 382; A Cathrein, *op. cit.* 1882 (i.), p. 169. F. Penck, *Sitzb. Bayer. Akad. Math. Phys.* 1880, p. 461. A. Wichmann, *Q. J. Geol. Soc.* xxxv. p. 156.

[3] *Acad. Roy. Belgique*, xli. (1877). See also his paper on the composition and structure of the phyllades of the Ardennes, *Bull. Mus. Roy. Belg.* iii., (1884), p. 231.

A number of varieties of Clay-slate are recognised. Roofing slate (Dachschiefer) includes the finest, most compact, homogeneous and durable kinds, suitable for roofing houses or the manufacture of tables, chimney-pieces, writing-slates, &c.; it occurs in the Silurian and Devonian formations of Central and Western Europe. Anthracitic-slate (anthracite-phyllite, alum-slate), dark carbonaceous slate with much iron-disulphide. Bands of this nature sometimes run through a clay-slate region. The carbonaceous material arises from the alteration of the remains of plants (fucoids) or animals (frequently graptolites). The marcasite so abundantly associated with these organisms decomposes on exposure, and the sulphuric acid produced, uniting with the alumina, potash, and other bases of the surrounding rocks, gives rise to an efflorescence of alum, or the decomposition produces sulphurous springs like those of Moffat. The name Greywacke-slate has been applied to extremely fine-grained, hard, shaly, more or less micaceous and sandy bands, associated with greywacke among the older Palæozoic rocks. Whet-slate, Novaculite, Hone-stone, is an exceedingly hard fine-grained siliceous rock, some varieties of which derive their economic value from the presence of microscopic crystals of garnet. The various forms of altered clay-slate are described at p. 179 among the metamorphic rocks.

Porcellanite (Argillite) or baked shale—a name applied to the exceedingly indurated sometimes partially fused condition which shales are apt to assume in contact with dykes and intrusive sheets or bosses. For an account of this form of contact-metamorphism see p. 600.

3. Volcanic Fragmental Rocks—Tuffs.

This section comprises all deposits which have resulted from the comminution of volcanic rocks. They thus include (1) those which consist of the fragmentary materials ejected from volcanic foci, or the true ashes and tuffs; and (2) some rocks derived from the superficial disintegration of already erupted and consolidated volcanic masses. Obviously the second series ought properly to be classed with the sandy or clayey rocks above described, since they have been formed in the same way. In practice, however, these detrital reconstructed rocks cannot always be certainly distinguished from those which have been formed by the consolidation of true volcanic dust and sand. Their chemical and lithological characters, both megascopic and microscopic, are occasionally so similar, that their respective modes of origin have to be decided by other considerations, such as the occurrence of lapilli, bombs, or slags in the truly volcanic series, and of well water-worn pebbles of volcanic rocks in the other. Attention to these features, however, usually enables the geologist to make the distinction, and to perceive that the number of instances where he may be in doubt is less than might be supposed. Only a comparatively small number of the rocks classed here are not true volcanic ejections.[1]

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[1] For a classification of tuffs and tuffaceous deposits see E. Reyer, *Jahrb. K. K. Geol. Reichsanst.* xxxi. (1881), p. 57.

Referring to the account of volcanic action in Book III. Part I. Sect. i., we may here merely define the use of the names by which the different kinds of ejected volcanic materials are known.

Volcanic Blocks—angular, sub-angular, round, or irregularly-shaped masses of lava, several feet in diameter, sometimes of uniform texture throughout, as if they were large fragments dislodged by explosion from a previously consolidated rock, sometimes compact in the interior and cellular or slaggy outside.

Bombs—round, elliptical, or discoidal pieces of lava from a few inches up to one or more feet in diameter. They are frequently cellular internally, while the outer parts are fine-grained. Occasionally they consist of a mere shell of lava with a hollow interior like a bomb-shell, or of a casing of lava enclosing a fragment of rock. Their mode of origin is explained in Book III. Part I. Sect. i. § 1.

Lapilli (rapilli)—ejected fragments of lava, round, angular, or indefinite in shape, varying in size from a pea to a walnut. Their mineralogical composition depends upon that of the lava from which they have been thrown up. Usually they are porous or finely vesicular in texture.

Volcanic Sand, Volcanic Ash—the finer detritus erupted from volcanic orifices, consisting partly of rounded and angular fragments up to about the size of a pea derived from the explosion of lava within eruptive vents, partly of vast quantities of microlites and crystals of some of the minerals of the lava. The finest dust is in a state of extremely minute subdivision. When examined under the microscope, it is sometimes found to consist not only of minute crystals and microlites, but of volcanic glass, which may be observed adhering to the microlites or crystals round which it flowed when still part of the fluid lava. The presence of minutely cellular fragments is characteristic of most volcanic fragmental rocks, and this structure may commonly be observed in the microscopic fragments and filaments of glass.

When these various materials are allowed to accumulate, they become consolidated and receive distinctive names. In cases where they fall into the sea or into lakes, they are liable at the outer margin of their area to be mingled with, and insensibly to pass into ordinary non-volcanic sediment. Hence we may expect to find transitional varieties between rocks formed directly from the results of volcanic explosion and ordinary sedimentary deposits.

Volcanic Conglomerate—a rock composed mainly or entirely of rounded or sub-angular fragments, chiefly or wholly of volcanic rocks, in a paste of the same materials, usually exhibiting a stratified arrangement, and often found intercalated between successive sheets of lava. Conglomerates of this kind may have been formed by the accumulation of rounded materials ejected from volcanic vents ; or as the result of the aqueous erosion of previously solidified lavas, or by a combination of both these processes. Well-rounded and smoothed stones almost certainly indicate long-continued water-action, rather than trituration in a volcanic vent. In the Western Territories of the United States vast tracts of country are covered with masses of such conglomerate, sometimes 2000 feet thick. Captain Dutton has shown that similar deposits are in course of formation there now, merely by the influence of disintegration upon exposed lavas.[1]

Volcanic conglomerates receive different names according to the nature of the component fragments; thus we have *basalt-conglomerates*, where these fragments are wholly or mainly of basalt, *trachyte-conglomerates*, *porphyrite-conglomerates*, *phonolite-conglomerates*, &c.

Volcanic Breccia resembles Volcanic Conglomerate, except that the stones are angular. This angularity indicates an absence of aqueous erosion, and, under the circumstances in which it is found, usually points to immediately adjacent volcanic explosions. There is a great variety of breccias, as *basalt-breccia*, *diabase-breccia*, &c.

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[1] 'High Plateaux of Utah,' p. 77.

Volcanic Agglomerate—a tumultuous assemblage of blocks of all sizes up to masses several yards in diameter, met with in the "necks" or pipes of old volcanic orifices. The stones and paste are commonly of one or more volcanic rocks, such as felsite, porphyrite or basalt, but they include also fragments of the surrounding rocks, whatever these may be, through which the volcanic orifice has been drilled. As a rule, agglomerate is devoid of stratification ; but sometimes it includes portions which have a more or less distinct arrangement into beds of coarser and finer detritus, often placed on end, or inclined in different directions at high angles, as described in Book IV. Part VII. Sect. i. § 4.

Volcanic Tuff.—This general term may be made to include all the finer kinds of volcanic detritus, ranging, on the one hand, through coarse gravelly deposits into conglomerates, and on the other, into exceedingly compact fine-grained rocks, formed of the finest and most impalpable kind of volcanic dust. Some modern tuffs are full of microlites, derived from the lava which was blown into dust. Others are formed of small rounded or angular grains of different lavas, with fragments of various rocks through which the volcanic funnels have been drilled. The tuffs of earlier geological periods have often been so much altered, that it is difficult to state what may have been their original condition. The absence of microlites and glass in them is no proof that they are not true tuffs ; for the presence of these bodies depends upon the nature of the lavas. If the latter were not vitreous and microlitic, neither would be the tuffs derived from them. In the Carboniferous volcanic area of Central Scotland, the tuffs are made up of débris and blocks of the basaltic lavas, and, like these, are not microlitic, though in some places they abound in fragments of the basic glass called palagonite. (Fig. 23, and *infra*, p. 138.)

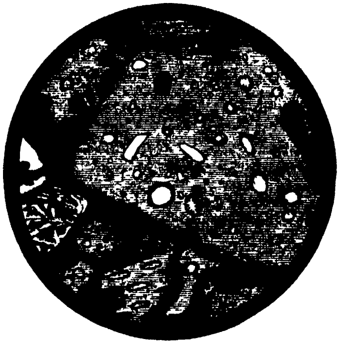

Fig. 23.—Microscopic Structure of Carboniferous Palagonite Tuff from Burntisland Fife.

Tuffs have consolidated sometimes under water, sometimes on dry land. As a rule, they are distinctly stratified. Near the original vents of eruption they commonly present rapid alternations of finer and coarser detritus, indicative of successive phases of volcanic activity. They necessarily shade off into the sedimentary formations with which they were contemporaneous. Thus, we have tuffs passing gradually into shale, limestone, sandstone, &c. The intermediate varieties have been called *ashy shale, tuffaceous shale*, or *shaley tuff*, &c. From the circumstances of their formation, tuffs frequently preserve the remains of plants and animals, both terrestrial and aquatic. Those of Monte Somma contain fragments of land-plants and shells. Some of those of Carboniferous age in Central Scotland have yielded crinoids, brachiopods, and other marine organisms. Like the other fragmentary volcanic rocks, the tuffs may be subdivided according to the nature of the lava from the disintegration of which they have been formed. Thus we have *felsite-tuffs, trachyte-tuffs, basalt-tuffs, pumice-tuffs, porphyrite-tuffs*, &c. A few varieties with special characteristics may be mentioned here.[1]

Trass—a pale yellow or grey rock, rough to the feel, composed of an earthy or compact pumiceous dust, in which fragments of pumice, trachyte, greywacke, basalt, carbonized wood, &c., are imbedded. It has filled up some of the valleys of the Eifel, where it is largely quarried as a hydraulic mortar.

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[1] On the occurrence and structure of tuffs, see J. C. Ward, *Q. J. Geol. Soc.* xxxi. p. 388 ; Reyer, *Jahrb. Geol. Reichsanst.* 1881, p. 57 ; Geikie, *Trans. Roy. Soc. Edin.* xxix. ; Vogelsang, *Z. Deutsch. Geol. Ges.* xxiv. p. 543 ; Penck, *op. cit.* xxxi. p. 504. On the basalt-tuffs of Scania, F. Eichstadt, *Sveriges Geol. Undersökn*, ser. c. No. 58 (1883). On the metamorphism of tuffs into lava-like rocks, see Dutton's 'High Plateaux of Utah' (U. S. Geograph. and Geol. Survey of Rocky Mounts.), 1880, p. 79.

Peperino—a dark-brown, earthy or granular tuff, found in considerable quantity among the Alban Hills near Rome, and containing abundant crystals of augite, mica, leucite, magnetite, and fragments of crystalline limestone, basalt, and leucite-lava.

Palagonite-Tuff—a bedded aggregate of dust and fragments of basaltic lava, among which are conspicuous angular pieces and minute granules of the pale yellow, green, red, or brown basic glass called palagonite. This vitreous substance is intimately related to the basalts (p. 172). It appears to have gathered within volcanic vents and to have been emptied thence, not in streams, but by successive aeriform explosions, and to have been subsequently more or less altered. The percentage composition of a specimen from the typical locality, Palagonia, in the Val di Noto, Sicily, was estimated by Sartorius von Waltershausen to be: silica, 41·26; alumina, 8·60; ferric oxide, 25·32; lime, 5·59; magnesia, 4·84; potash, 0·54; soda, 1·06; water, 12·79. This rock is largely developed among the products of the Icelandic and Sicilian volcanoes; it occurs also in the Eifel and in Nassau. It has been found to be one of the characteristic features of tuffs of Carboniferous age in Central Scotland[1] (Fig. 23).

Schalstein.—Under this name, German petrographers have placed a variety of green, grey, red, or mottled fissile rocks, impregnated with carbonate of lime. They are interstratified with the Devonian formations of Nassau, the Harz and Devonshire, and with the Silurian rocks of Bohemia. They sometimes contain fragments of clay-slate, and are occasionally fossiliferous. They present amygdaloidal and porphyritic, as well as perfectly laminated structures. Probably they are in most cases true diabase-tuffs, but sometimes they may be forms of diabase-lavas, which, like the stratified formations in which they lie, have undergone alteration, and in particular have acquired a more or less distinctly fissile structure, as the result of lateral pressure and internal crushing.[2]

4. Fragmental Rocks of Organic Origin.

This series includes deposits formed either by the growth and decay of organisms *in situ*, or by the transport and subsequent accumulation of their remains. These may be conveniently grouped, according to their predominant chemical ingredient, into Calcareous, Siliceous, Phosphatic, Carbonaceous, and Ferruginous.

1. CALCAREOUS.—Besides the calcareous formations which occur among the stratified crystalline rocks as results of the deposition of chemical precipitates (p. 149), a more important series is derived from the remains of living organisms, either by growth on the spot or by transport and accumulation as mechanical sediment. To by far the larger part of the limestones intercalated in the rocky framework of our continents, an organic origin may with probability be assigned. It is true, as has been above mentioned (p. 122), that limestone, formed of the remains of animals or plants, is liable to an internal crystalline rearrangement, the effect of which is to obliterate the organic structure. Hence in many of the older limestones, no trace of any fossils can be detected, and yet these rocks were almost certainly formed of organic remains. An attentive microscopic study of organic calcareous structures, and of the mode of their replacement by crystalline calcite, sometimes detects indications of former organisms, even in the midst of thoroughly crystalline materials.[3]

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[1] *Trans. Roy. Soc. Edin.* xxix. p. 514.

[2] C. Koch, *Jahrb. Ver. Nat. Nassau*, xiii. (1858), 216, 238. J. A. Phillips, *Q. J. Geol. Soc.* xxxii. p. 155, xxxiv. p. 471.

[3] Sorby, *Address to Geol. Society*, February, 1879, and the paper of Messrs. Cornish and Kendall, cited *ante*, p. 122. Gümbel has suggested that the different durability of the calcite and aragonite organic forms may be due rather to structure than mineral composition.

Limestone, composed of the remains of calcareous organisms, is found in layers which range from mere thin laminæ up to massive beds, several feet or even yards in thickness. In some instances, such as that of the Carboniferous or Mountain limestone of Britain and Belgium, and that of the Coal-measures in Wyoming and Utah, it occurs in continuous superposed beds to a united thickness of several thousand feet, and extends for hundreds of square miles, forming a rock out of which picturesque gorges, hills, and table-lands have been excavated.

Limestones of organic origin present every gradation of texture and structure, from mere soft calcareous mud or earth, evidently composed of entire or crumbled organisms up to solid compact crystalline rock, in which indications of an organic source can hardly be perceived. Mr. Sorby, in the address already cited, called renewed attention to the importance of the form in which carbonate of lime is built up into animal structures. Quoting the opinion of Rose expressed in 1858, that the diversity in the state of preservation of different shells might be due to the fact that some of them had their lime as calcite, others as aragonite, he showed that this opinion is amply supported by microscopic examination. Even in the shells of a recent raised beach, he observed that the inner aragonite layer of the common mussel had been completely removed, though the outer layer of calcite was well preserved. In some shelly limestones containing casts, the aragonite shells have alone disappeared, and where these still remain represented by a calcareous layer, this has no longer the original structure, but is more or less coarsely crystalline, being in fact a pseudomorph of calcite after aragonite, and quite unlike contiguous calcite shells, which retain their original microscopical and optical characters.[1]

The following list comprises some of the more distinctive and important forms of organically-derived limestones.

Shell-Marl—a soft, white, earthy, or crumbling deposit, formed in lakes and ponds by the accumulation of the remains of shells and *Entomostraca* on the bottom. When such calcareous deposits become solid compact stone they are known as *fresh-water* (*lacustrine*) *limestones*. These are generally of a smooth texture, and either dull white, pale grey, or cream-coloured, their fracture slightly conchoidal, rarely splintery.

Lumachelle—a compact, dark grey or brown limestone, charged with ammonites or other fossil shells, which are sometimes iridescent, giving bright green, blue, orange, and dark red tints (fire-marble).

Calcareous (Foraminiferal) Ooze—a white or grey calcareous mud, of organic origin, found covering vast areas of the floor of the Atlantic and other oceans, and formed mostly of the remains of *Foraminifera*, particularly of forms of the genus *Globigerina* (Fig. 24). Further account of this and other organic deep-sea deposits is given in Book III. Part II. Section iii.

Shell-Sand—a deposit composed in great measure or wholly of comminuted shells, found commonly on a low shelving coast exposed to prevalent on-shore winds. When thrown above the reach of the waves and often wetted by rain, or by trickling runnels of water, it is apt to become consolidated into a mass, owing to the solution and redeposit of lime round the grains of shell (p. 122).

Coral-rock—a limestone formed by the continuous growth of coral-building polyps. This substance affords an excellent illustration of the way in which organic structure may be effaced from a limestone entirely formed of the remains of once living animals. Though the skeletons of the reef-building corals remain distinct on the upper surface, those of their predecessors beneath them are gradually obliterated by the passage through them of percolating water, dissolving and redepositing calcium carbonate. We can thus understand how a mass of crystalline limestone may have been produced from one formed out of organic remains, without the action of any subterranean heat, but merely by the permeation of water from the surface.[1]

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[1] The student will find the address from which these citations are made full of suggestive matter in regard to the origin and subsequent history of limestones.

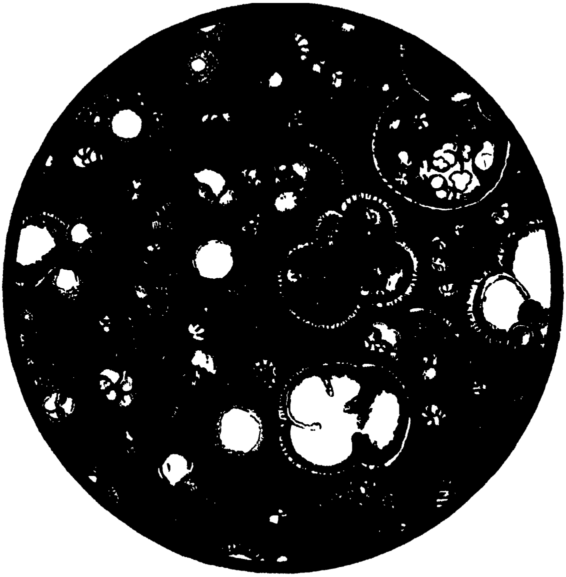

Fig. 24.—Foraminiferal (Globigerina) Ooze, dredged by the *Challenger* Expedition in Lat. 50° 1 S., Long. 123° 4′ E., from a depth of 1800 fathoms (magnified 50 Diameters).

Chalk—a white soft rock, meagre to the touch, soiling the fingers, formed of a fine calcareous flour derived from the remains of *Foraminifera*, echinoderms, mollusks, and other marine organisms. By making thin slices of the rock and examining them under the microscope, Sorby has found that Foraminifera, particularly *Globigerina*, and single detached cells of comparatively shallow-water forms, probably constitute less than half of the rock by bulk (Fig. 22), the remainder consisting of detached prisms of the outer calcareous layer of *Inoceramus*, fragments of *Ostrea*, *Pecten*, echinoderms, spicules of sponges, &c. It is not quite like any known modern deep-sea deposit. A microscopic investigation of chalk from the neighbourhood of Lille showed that, besides the usual organic constituents, the rock contains minute grains and crystals of quartz, tourmaline, zircon, rutile, garnet and felspars,[2] these minerals being among the most widely diffused and persistent ingredients in the finer sediments that are derived from the denudation of crystalline rocks (see p. 129).

Crinoidal (Encrinite) Limestone—a rock composed in great part of crystalline joints of encrinites, with *Foraminifera*, corals, and mollusks. It varies in colour from white or pale grey, through shades of bluish-grey (sometimes yellow or brown, less commonly red) to a dark grey or even black colour. It is abundant among Palæozoic formations, being in Western Europe especially characteristic of the lower part of the Carboniferous system.

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[1] See Dana's 'Coral and Coral Islands,' p. 354; also the account of the Devonian and Carboniferous limestones in the present volume. Dupont has shown that many of the massive limestones of Belgium have been formed by reef-like masses of *Stromatopora* or allied organisms.

[2] L. Cayeux, *Ann. Soc. Géol. Nord.* xvii. (1890), p. 283.

2. SILICEOUS.—Silica is directly eliminated from both fresh and salt water by the vital growth of plants and animals. (Book III. Part II. Section iii.)

Diatom-earth, Tripolite (Infusorial earth, Kieselguhr)—a siliceous deposit formed chiefly of the frustules of diatoms, laid down both in salt and in fresh water. Wide areas of it are now being deposited on the bed of the South Pacific (*Diatom-ooze*, Fig. 181). In Virginia, United States, an extensive tract occurs covered with diatom-earth to a depth of 40 feet. It likewise underlies peat-mosses, probably as an original lake-deposit. It is used as *Tripoli powder* for polishing purposes (see p. 481).

Radiolarian ooze—a pale chalk-like abysmal marine deposit consisting mainly of the remains of siliceous radiolarians and diatoms. It is further referred to in Book III. Part II. Section iii.

Flint (Silex, Feuerstein)—a grey or black, excessively compact rock, with the hardness of quartz and a perfect conchoidal fracture, its splinters being translucent on the edges. Consists of an intimate mixture of crystalline insoluble silica and of amorphous silica soluble in caustic potass. Its dark colour, which can be destroyed by heat, arises chiefly from the presence of carbonaceous matter. Flint occurs principally as nodules, dispersed in layers through the Upper Chalk of England and the north-west of Europe. It frequently encloses organisms such as sponges, echini and brachiopods. It has been deposited from sea-water, at first through organic agency, and subsequently by direct chemical precipitation round the already deposited silica. (Book III. Part II. Sect. iii.) Chert (phtanite) is a name applied to impure calcareous varieties of flint, in layers and nodules which are found among the Palæozoic and later formations, especially but not exclusively in limestones.[1] In some cases, as in the spicules of sponges, the silica has had a directly organic origin, having been secreted from sea-water by the living organisms; in other cases, where for example we find a calcareous shell, or echinus, or coral, converted into silica, it would seem that the substitution of silica for calcium-carbonate has been effected by a process of chemical pseudomorphism, either after or during the formation of the limestone. The vertical ramifying masses of flint in Chalk show that the calcareous ooze had to some extent accumulated before the segregation of these masses.[2]

3. PHOSPHATIC.—A few invertebrata contain phosphate of lime. Among these may be mentioned the brachiopods *Lingula* and *Orbicula*,[3] also *Conularia*, *Serpulites*, and some recent and fossil crustacea. The shell of the recent *Lingula ovalis* was found by Hunt to contain, after calcination, 61 per cent of fixed residue, which consisted of 85·70 per cent of phosphate of lime; 11·75 carbonate of lime, and 2·80 magnesia. The bones of vertebrate animals likewise contain about 60 per cent of phosphate of lime, while their excrement sometimes abounds in the same substance. Hence deposits rich in phosphate of lime have resulted from the accumulation of animal remains from Silurian times up to the present day. Associated with the Bala limestone, in the Lower Silurian series of North Wales is a band composed of concretions cemented in a black, graphitic, slightly phosphatic matrix, and containing usually 64 per cent of phosphate of lime (phosphorite).[4] The tests of the trilobites and other organisms among the Cambrian rocks of Wales also contain phosphate of lime, sometimes to the extent of 20 per cent.[5] Phosphatic, though certainly far inferior in extent and importance to cal-

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[1] Consult Hull and Hardman, *Trans. Roy. Dublin Soc.* i. (1878), p. 71. Renard, *Bull. Acad. Roy. Belgique*, 2d ser. vol. xlvi. p. 471; Sollas, *Ann. Mag. Nat. Hist.* vii. (1881), p. 141; *Scientific Proc. Roy. Dublin Soc.* vi. (1887), part i. G. J. Hinde, *Geol. Mag.* 1887, p. 435. Bands of radiolarian chert occupy persistent horizons among the Lower Silurian rocks of southern Scotland.

[2] On formation of chalk-flints, see Book III. Part II. Section iii. § 3.

[3] Sterry Hunt, *Amer. Journ. Soc.* xvii. (1854), p. 236. Logan's 'Geology of Canada,' 1863, p. 461.

[4] D. C. Davies, *Q. J. Geol. Soc.* xxxi. p. 357. [5] Hicks, *op. cit.* p. 368.

careous, and even to siliceous, formations, are often of singular geological interest. The following examples may serve as illustrations.[1]

Guano—a deposit consisting mainly of the droppings of sea-fowl, formed on islands in rainless tracts off the western coasts of South America and of Africa. It is a brown, light, powdery substance with a peculiar ammoniacal odour, and occurs in deposits sometimes more than 100 feet thick. Analyses of American guano give—combustible organic matter and acids, 11·3; ammonia (carbonate, urate, &c.), 31·7; fixed alkaline salts, sulphates, phosphates, chlorides, &c., 8·1; phosphates of lime and magnesia, 22·5; oxalate of lime, 2·6; sand and earthy matter, 1·6; water, 22·2. This remarkable substance is highly valuable as a source of artificial manures. (Book III. Part II. Section iii.)

Bone-Breccia—a deposit consisting largely of fragmentary bones of living or extinct species of mammalia, found sometimes under stalagmite on the floors of limestone caverns, more or less mixed with earth, sand, or lime. In some older geological formations, bone-beds occur, formed largely of the remains of reptiles or fishes, as the "Lias bone-bed," and the "Ludlow bone-bed."

Coprolitic nodules and **beds**[2]—are formed of the accumulated excrement (coprolites) of vertebrated animals. Among the Carboniferous shales of the basin of the Firth of Forth, coprolitic nodules are abundant, together with the bones and scales of the larger ganoid fishes which voided them: abundance of broken scales and bones of the smaller ganoids can usually be observed in the coprolites. Among the Lower Silurian rocks of Canada, numerous phosphatic nodules, supposed to be of coprolitic origin, occur.[3] The phosphatic beds of the Cambridgeshire Cretaceous rocks are now largely worked as a source of artificial manure. In popular and especially commercial usage, the word "coprolitic" is applied to nodular deposits which can be worked for phosphate of lime, though they may contain few or no true coprolites.

Phosphatic Chalk.—In the Chalk of France and Belgium, more sparingly in that of England, certain layers occur where the original calcareous matter has been replaced to a considerable extent by phosphate of lime. Such bands have frequently a brownish tint, which on examination is found to result from the abundance of minute brown grains composed mainly of phosphate. The foraminifera and other minuter or fragmentary fossils have been changed into this brown substance. The proportion of phosphate of lime ranges up to 45 per cent or more.[4]

4. CARBONACEOUS.—The formations here included have almost always resulted from the decay and entombment of vegetation on the spot where it grew, sometimes by the drifting of the plants to a distance and their consolidation there. (See Book III. Part II. Section iii. § 3.) In the latter case, they may be mingled with inorganic sediment, so as to pass into carbonaceous shale.

Peat—vegetable matter, more or less decomposed and chemically altered, found throughout temperate climates in boggy places where marshy plants grow and decay. It varies from a pale yellow or brown fibrous substance, like turf or compressed hay, in which the plant-remains are abundant and conspicuous, to a compact dark brown or black material, resembling black clay when wet, and some varieties of lignite when dried. The nature and proportions of the constituent elements of peat, after being dried at 100° C., are illustrated by the analysis of an Irish example which gave—carbon, 60·48; hydrogen, 6·10; oxygen, 32·55; nitrogen, 0·88; while the ash was 3·30.

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[1] For an exhaustive account of deposits of phosphate of lime, see R. A. F. Penrose Jr., *Bull. U.S. Geol. Surv.* No. 46, 1888, also *postea*, Book. III. Part II. Sect. iii. § 3.

[2] On the origin of phosphatic nodules and beds, see Gruner, *Bull. Soc. Géol. France*, xxviii. (2nd ser.), p. 62. Martin, *op. cit.* iii. (3rd ser.), p. 273.

[3] Logan's 'Geology of Canada,' p. 461.

[4] See A. F. Renard and J. Cornet, *Bull. Acad. Roy. Belgique*, xxi. (1891), p. 126. A. Strahan, *Quart. Journ. Geol. Soc.* xlvii. (1891).

There is always a large proportion of water which cannot be driven off even by drying the peat. In the manufacture of compressed peat for fuel this constituent, which of course lessens the value of the peat as compared with an equal weight of coal, is driven off to a great extent by chopping the peat into fine pieces, and thereby exposing a large surface to evaporation. The ash varies in amount from less than 1·00 to more than 65 per cent, and consists of sand, clay, ferric oxide, sulphuric acid, and minute proportions of lime, soda, potash and magnesia.[1] Under a pressure of 6000 atmospheres peat is converted into a hard, black, brilliant substance having the physical aspect of coal, and showing no trace of organic structure.[2]

Lignite (Brown Coal)—compact or earthy, compressed and chemically altered vegetable matter, often retaining a lamellar or ligneous texture, with stems showing woody fibre crossing each other in all directions. It varies from pale brown or yellow to deep brown or black. Some shade of brown is the usual colour, whence the name *Brown Coal*, by which it is often known. It contains from 55 to 75 per cent of carbon, has a specific gravity of 0·5 to 1·5, burns easily to a light ash with a sooty flame and a strong burnt smell. It occurs in beds chiefly among the Tertiary strata, under conditions similar to those in which coal is found in older formations. It may be regarded as a stage in the alteration and mineralization of vegetable matter, intermediate between peat and true coal.

Coal—a compact, usually brittle, velvet-black to pitch-black, iron-black, or dull, sometimes brownish rock, with a greyish-black or brown streak, and in some varieties a distinctly cubical cleavage, in others a conchoidal fracture. It contains from 75 to 90 per cent of carbon, and a small percentage of sulphur, generally in the form of iron-disulphide. It has a specific gravity of 1·2–1·35, and burns with comparative readiness, giving a clear flame, a strong aromatic or bituminous smell, some varieties fusing and caking into cinder, others burning away to a mere white or red ash. Though it consists of compressed vegetation, no trace of organic structure is usually apparent.[3] An attentive examination, however, will often disclose portions of stems, leaves, &c., or at least of carbonized woody fibre. Some kinds are almost wholly made up of the spore-cases of lycopodiaceous plants (Fig. 25). There is reason to believe that different varieties of coal may have arisen from original diversities in the nature of the vegetation out of which they were formed. The accompanying table shows the chemical gradation between unaltered vegetation and the more highly mineralized forms of coal.

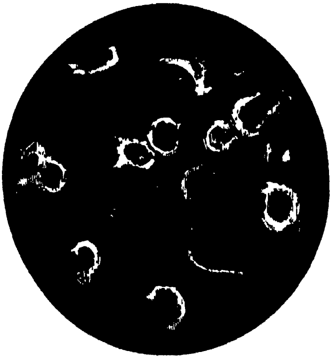

Fig. 25.—Microscopic Structure of Dalkeith Coal, showing Lycopodiaceous Sporangia (magnified 200 Diameters).

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[1] See Senft's 'Humus-, Marsch-, Torf- und Limonit-bildungen,' Leipzig, 1862. J. J. Fruh, 'Ueber Torf und Dopplerit,' Zurich, 1883, and the various memoirs quoted *postea*, p. 478.

[2] Spring, *Bull. Acad. Roy. Bruxelles*, xlix. (1880), p. 367.

[3] On the influence of pressure on the formation of coal, see Frémy, *Compt. rend.* 20th May 1879. Spring, *Bull. Acad. Roy. Bruxelles*, 1880, p. 367.

TABLE SHOWING THE GRADUAL CHANGE IN COMPOSITION FROM WOOD TO CHARCOAL.[1]

Substance.	Carbon.	Hydrogen	Oxygen.	Disposable Hydrogen, *i.e.*, over and above what is required to form water.
1. Wood (mean of several analyses .	100	12·18	83·07	1·80
2. Peat (,, ,, ,,) .	100	9·85	55·67	2·89
3. Lignite (mean of 15 varieties) . .	100	8·37	42·42	3·07
4. Ten-yard coal of S. Staffordshire basin	100	6·12	21·23	3·47
5. Steam coal from the Tyne . . .	100	5·91	18·32	3·62
6. Pentrefelin coal of S. Wales . .	100	4·75	5·28	4·09
7. Anthracite from Pennsylvania, U.S.	100	2·84	1·74	2·63

Coal occurs in seams or beds intercalated between strata of sandstone, shale, fireclay, &c., in geological formations of Palæozoic, Secondary, and Tertiary age. It should be remembered that the word coal is rather a popular than a scientific term, being indiscriminately applied to any dense, black mineral substance capable of being used as fuel. Strictly employed, it ought only to be used with reference to beds of fossilized vegetation, the result either of the growth of plants on the spot or of the drifting of them thither.

The following analyses show the chemical composition of peat, lignite, and some of the principal varieties of coal[2]:—

	Peat.	*Lignite.*	*Caking Coal.*	*Non-Caking Coal.*	*Cannel Coal.*	*Anthracite.*
	Devonshire.	Bovey Tracey, Devon.	Northumberland.	S. Staffordshire.	Wigan.	S. Wales.
Carbon	54·02	66·31	78·69	78·57	80·07	90·39
Hydrogen	5·21	5·63	6·00	5·29	5·53	3·28
Oxygen	28·18	22·86	10·07	12·88	8·08	2·98
Nitrogen	2·30	0·57	2·37	1·84	2·12	0·83
Sulphur	0·56	2·36	1·51	0·39	1·50	0·91
Ash	9·73	2·27	1·36	1·03	2·70	1·61
Specific gravity . .	0·850	1·129	1·259	1·278	1·276	1·392

These analyses are exclusive of water, which in the peat amounted to 25·56, and in the lignite to 34·66 per cent.

Anthracite—the most highly mineralized form of vegetation—is an iron-black to velvet-black substance, with a strong metalloidal to vitreous lustre, hard and brittle, containing over 90 per cent of carbon, with a specific gravity of 1·35–1·7. It kindles with difficulty, and in a strong draught burns without fusing, smoking, or smelling, but giving out a great heat. It is a coal from which the bituminous parts have been eliminated. It occurs in beds like ordinary coal, but in positions where probably it has been subjected to some change whereby its volatile constituents have been expelled. It is found largely in South Wales, and sparingly in the Scottish coal-fields where the ordinary coal-seams have been approached by intrusive masses of igneous rock. It is largely developed in the great coal-field of Pennsylvania. Some Lower Silurian shales are black from diffused anthracite, and have in consequence led to fruitless searches for coal.

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[1] Percy's 'Metallurgy,' vol. i. p. 268.

[2] From Percy's 'Metallurgy,' vol. i.

Oil-shale (*Brandschiefer*)—shale containing such a proportion of hydrocarbons as to be capable of yielding mineral oil on slow distillation. This substance occurs as ordinary shales do, in layers or beds, interstratified with other aqueous deposits, as in the Scottish coal-fields. It is in a geological sense true shale, and owes its peculiarity to the quantity of vegetable (or animal) matter which has been preserved among its inorganic constituents. It consists of fissile argillaceous layers, highly impregnated with bituminous matter, passing on one side into common shale, on the other into cannel or parrot coal. The richer varieties yield from 30 to 40 gallons of crude oil to the ton of shale. They may be distinguished from non-bituminous or feebly bituminous shales (throughout the shale districts of Scotland), by the peculiarity that a thin paring curls up in front of the knife, and shows a brown lustrous streak. Some of the oil-shales in the Lothians are crowded with the valves of ostracod crustaceans, besides scales, coprolites, &c., of ganoid fishes. It is possible that the bituminous matter may in some cases have resulted from animal organisms, though the abundance of plant remains indicates that it is probably in most cases of vegetable origin. Under the name "pyroschists" Sterry Hunt classed the clays or shales (of all geological ages) which are hydrocarbonaceous, and yield by distillation volatile hydrocarbons, inflammable gas, &c.

Petroleum, a general term, under which is included a series of natural mineral oils. These are fluid hydrocarbon compounds, varying from a thin, colourless, watery liquidity to a black, opaque, tar-like viscidity, and in specific gravity from 0·8 to 1·1. The paler, more limpid varieties are generally called naphtha, the darker, more viscid kinds mineral tar, while the name petroleum, or rock-oil, has been more generally applied to the intermediate kinds. Petroleum occurs sparingly in Europe. A few localities for it are known in Britain. It is found in large quantity along the country stretching from the Carpathians, through Gallicia and Moldavia, also at Baku on the Caspian.[1] The most remarkable and abundant display of the substance, however, is in the so-called oil-regions of North America, particularly in Western Canada and Northern Pennsylvania, where vast quantities of it have been obtained in recent years. In Pennsylvania it is found especially in certain porous beds of sandstone or "sand-rocks," which occur as low down as the Old Red Sandstone, or even as the top of the Silurian system. In Canada it is largely present in still lower strata. Its origin in these ancient formations, where it cannot be satisfactorily connected with any destructive distillation of coal, is still an unsolved problem.

Asphalt—a smooth, brittle, pitch-like, black or brownish-black mineral, having a resinous lustre and conchoidal fracture, streak paler than surface of fracture, and specific gravity of 1·0 to 1·68. It melts at about the temperature of boiling water, and can be easily kindled, burning with a bituminous odour and a bright but smoky flame. It is composed chiefly of hydrocarbons, with a variable admixture of oxygen and nitrogen. It occurs sometimes in association with petroleum, of which it may be considered a hardened oxidized form, sometimes as an impregnation filling the pores or chinks of rocks, sometimes in independent beds. In Britain it appears as a product of the destructive distillation of coals and carbonaceous shales by intrusive igneous rocks, as at Binny Quarry, Linlithgowshire, but also in a number of places where its origin is not evident, as in the Cornish and Derbyshire mining districts, and among the dark flagstones of Caithness and Orkney, which are laden with fossil fishes. At Seyssel (Département de l'Ain) it forms a deposit 2500 feet long and 800 feet broad, which yields 1500 tons annually. It exudes in a liquid form from the ground round the borders of the Dead Sea. In Trinidad it forms a lake 1½ mile in circumference, which is cool and solid near the shore, but increases in temperature and softness towards the centre.

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[1] Abich, *Jahrb. Geol. Reichsanst.* xxix. (1879), p. 165. Trautschold, *Zeitsch. Deutsch. Geol. Ges.* xxvi. (1874), p. 257. See *postea*, Book III. Part I. Sect. i. § 2 where other authorities are cited.

Graphite.—This mineral occurs in masses of sufficient size and importance to deserve a place in the enumeration of carbonaceous rocks. Its mineralogical characters have already (p. 67) been given. It occurs in distinct lenticular beds, and also diffused in minute scales, through slates, schists, and limestones of the older geological formations, as in Cumberland, Scotland, Canada, and Bohemia. It is likewise found occasionally as the result of the alteration of a coal seam by intrusive basalt, as at New Cumnock in Ayrshire.

5. FERRUGINOUS.—The decomposition of vegetable matter in marshy places and shallow lakes gives rise to certain organic acids, which, together with the carbonic acid so generally also present, decompose the ferruginous minerals of rocks and carry away soluble salts of iron. Exposure to the air leads to the rapid decomposition and oxidation of those solutions, which consequently give rise to precipitates, consisting partly of insoluble basic salts and partly of the hydrated ferric oxide. These precipitates, mingled with clay, sand, or other mechanical impurity, and also with dead and decaying organisms, form deposits of iron-ore. Operations of this kind appear to have been in progress from a remote geological antiquity. Hence ironstones with traces of associated organic remains belong to many different geological formations, and are being formed still.[1]

Bog Iron-Ore (Lake-ore, minerai des marais, Sumpferz)—a dark-brown to black, earthy, but sometimes compact mixture of hydrated peroxide of iron, phosphate of iron, and hydrated oxide of manganese, frequently with clay, sand, and organic matter. An ordinary specimen yielded, peroxide of iron, 62·59; oxide of manganese, 8·52; sand, 11·37; phosphoric acid, 1·50; sulphuric acid, traces; water and organic matter, 16·02 = 100·00. Bog iron-ore may either be formed *in situ* from still water, or may be laid down by currents in lakes. Of the former mode of formation, a familiar illustration is furnished by the "moor-band pan" or hard ferruginous crust, which in boggy places and on some ill-drained land, forms at the bottom of the soil, on the top of a stiff and tolerably impervious subsoil. Abundant bog-iron or lake-ore is obtained from the bottoms of some lakes in Norway and Sweden. It forms everywhere on the shallower slopes near banks of reeds, where there is no strong current of water, occurring in granular concretions (Bohnerz) that vary from the size of grains of coarse gunpowder up to nodules 6 inches in diameter, and forming layers 10 to 200 yards long, 5 to 15 yards broad, and 8 to 30 inches thick. These deposits are worked during winter by inserting perforated iron shovels through holes cut in the ice; and so rapidly do they accumulate, that instances are known where, after having been completely removed, the ore at the end of twenty-six years was found to have gathered again to a thickness of several inches. A layer of loose earthy ochre 10 feet thick is believed to have formed in 600 years on the floor of the Lake Tisken near the old copper mine of Falun in Sweden.[2] According to Ehrenberg, the formation of bog-ore is due, not merely to the chemical actions arising from the decay of organic matter, but to a power possessed by diatoms of separating iron from water and depositing it as hydrous peroxide within their siliceous framework.

Aluminous Yellow Iron-Ore is closely related to the foregoing. It is a mixture of yellow or pale brown, hydrated peroxide of iron, with clay and sand, sometimes with silicate of iron, hydrated oxide of manganese, and carbonate of lime, and occurs in dull, usually pulverulent grains and nodules. Occasionally these nodules may be observed to consist of a shell of harder material, within which the yellow oxide becomes progressively softer towards the centre, which is sometimes quite empty. Such concretions are known as ætites or eagle-stones. This ore occurs in the Coal-measures of Saxony and Silesia, also in the Harz, Baden, Bavaria, &c., and among the Jurassic rocks in England.

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[1] See Senft's work already (p. 143) cited, p. 168; also *postea*, Book III. Part II. Sect. iii.

[2] A. F. Thoreld, *Geol. Fören. Förhand. Stockholm*, iii. p. 20, *postea*, pp. 407, 483.

Clay-Ironstone (Sphærosiderite) has been already (p. 78) referred to. It occurs abundantly in nodules and beds in the Carboniferous system in most parts of Europe. The nodules are generally oval and flattened in form, varying in size from a small bean up to concretions a foot or more in diameter, and with an internal system of radiating cracks, often filled with calcite (Fig. 26). In many cases, they contain in the centre some organic substance, such as a coprolite, fern, cone, shell, or fish, that has served as a surface round which the iron in the water and the surrounding mud could be precipitated. Seams of clay-ironstone vary in thickness from mere paper-like partings up to beds several feet deep. The Cleveland seam in the middle Lias of Yorkshire is about 20 feet thick. In the Carboniferous system of Scotland certain seams known as *Black-band* contain from 10 to 52 per cent of coaly matter, and admit of being calcined with the addition of little or no fuel. They are sometimes crowded with organic remains, especially lamellibranchs (*Anthracosia*, *Anthracomya*, &c.) and fishes (*Rhizodus*, *Megalichthys*, &c.)

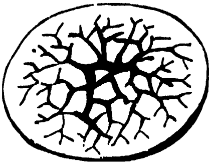

Fig. 26.—Septarian Nodule of Clay-ironstone.

A microscopic examination of some black-band ironstones reveals a very perfect oolitic structure, showing that the iron has either replaced an original calcareous oolite or has been precipitated in water having such a gentle movement as to keep the granules quietly rolling along, while their successive concentric layers of carbonate were being deposited. Mr. Sorby has observed in the Cleveland ironstones an abnormal form of oolitic structure, and remarks that one specimen bore evidence that the iron, mostly in the form of small crystals of the carbonate, had been introduced subsequently to the formation of the rock, as it had replaced some of the aragonite of the enclosed shells.[1]

The subjoined analyses show the composition of some varieties of clay-ironstones.[2]

	Clay iron-ore (Coal measures), Yorkshire.	Black Band (Carboniferous), Scotland.	Cleveland ore (Lias), Yorkshire.
Peroxide of iron	1·45	2·72	2·86
Protoxide of iron	36·14	40·77	43·02
Protoxide of manganese	1·38	—	0·40
Alumina	6·74	—	5·87
Lime	2·70	0·90	5·14 (zinc)
Magnesia	2·17	0·72	5·21
Potash	0·65	—	—
Silica	17·37	10·10	7·17
Carbonic acid	26·57	26·41	25·50
Phosphoric acid	0·34	—	1·81
Sulphuric acid	trace	—	—
Iron pyrites	0·10	—	—
Water	1·77	1·0	3·48
Organic matter	2·40	17·38	0·15
	99·78	100·00	100·61
Percentage of iron	29·12	34·60	35·46

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[1] Address to Geol. Soc. February 1879.

[2] See Percy's 'Metalurgy,' vol. ii. Bischof, 'Chem. und Phys. Geol.' supp. (1871), p. 65.

B. CRYSTALLINE, INCLUDING ROCKS FORMED FROM CHEMICAL PRECIPITATION.

This division consists mainly of chemical deposits, but includes also some which, originally formed of organic calcareous débris, have acquired a crystalline structure. The rocks included in it occur as laminæ and beds, usually intercalated among clastic formations, such as sandstone and shale. Sometimes they attain a thickness of many thousand feet, with hardly any interstratification of mechanically derived sediment. They are being formed abundantly at the present time by mineral springs and on the floor of inland seas; while on the bottom of lakes and of the main ocean, calcareous organic accumulations are in progress, which will doubtless eventually acquire a thoroughly crystalline structure like that of many limestones.

Ice.—So large an area of the earth's surface is covered with ice, that this substance deserves notice among geological formations. Ice is commonly and conveniently classified in two divisions, snow-ice and water-ice, according as it results from the compression and alternate melting and freezing of fallen snow, or from the freezing of the surface or bottom of sheets of water.

Snow-ice (see Book III. Part II. Sect. ii. § 5) is of two kinds. 1st, Fallen snow on mountain slopes above the snow-line gradually assumes a granular structure. The little crystalline needles and stars of ice are melted and frozen into rounded granules which form a more or less compact mass known in Switzerland as *Névé* or *Firn.* 2nd, When the granular névé slowly slides down into the valleys, it acquires a more compact crystalline structure and becomes *glacier-ice.* According to the researches of F. Klocke, glacier-ice is, throughout its mass, an irregular aggregate of distinct crystalline grains, the boundaries of which form the minute capillary fissures so often described.[1] Its structure thus closely corresponds to that of marble (p. 151). Glacier-ice in small fragments is white or colourless, and often shows innumerable fine bubbles of air, sometimes also fine particles of mud. In larger masses, it has a blue or green-blue tint, and displays a veined structure, consisting of parallel vertical veinings of white ice full of air-bubbles, and of blue clear ice without air-bubbles. Snow-ice is formed above the snow-line, but may descend in glaciers far below it. It covers large areas of the more lofty mountains of the globe, even in tropical regions. Towards the poles it descends to the sea, where large pieces break off and float away as icebergs.

Water-ice (see Book III. Part II. Sect. ii. § 5) is formed, 1st, by the freezing of the surface of fresh water (river-ice, lake-ice), or of the sea (ice-foot, floe-ice, pack-ice); this is a compact, clear, white or greenish ice. 2nd, by the freezing of the layer of water lying on the bottom of rivers, or the sea (bottom-ice, ground-ice, anchor-ice); this variety is more spongy, and often encloses mud, sand and stones.[2]

Rock-Salt (Sel gemme, Steinsalz, p. 79) occurs in layers or beds from less than an inch to many hundred feet in thickness. The salt deposits at Stassfurt, for example, are 1197 feet thick, of which the lowest beds comprise 685 feet of pure rock-salt, with thin layers of anhydrite ¼-inch thick dividing the salt at intervals of from one to eight inches. Still more massive are the accumulations of Sperenberg near Berlin, which have been bored through to a depth of 4200 feet, and those of Wieliczka in Gallicia which are here and there more than 4600 feet thick.

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[1] *Neues Jahrb.* 1881 (i.), p. 23. Grad and Dupré (*Ann. Club. Alp. Franc.* 1874) show how the characteristic structure of glacier-ice may be revealed by allowing coloured solutions to permeate it.

[2] On the properties of ice with some interesting geological bearings, see O. Pettersson, 'Vega-Expeditionens Vetenskapliga Iakttagelser,' vol. ii. p. 249, Stockholm, 1883.

The more insoluble salts (notably gypsum or anhydrite) are apt to appear in the lower parts of a saliferous series. When purest, rock-salt is clear and colourless, but usually is coloured red (peroxide of iron), sometimes green, or blue (chloride or silicate of copper). It varies in structure, being sometimes beautifully crystalline and giving a cubical cleavage; laminated, granular, or less frequently fibrous. It usually contains some admixture of clay, sand, anhydrite, bitumen, &c., and is often mixed with chlorides of magnesium, calcium, &c. In some places it is full of vesicles (not infrequently of cubic form) containing saline water; or it abounds with minute cavities filled with hydrogén, nitrogen, carbon-dioxide, or with some hydrocarbon gas. Occasionally remains of minute forms of vegetable and animal life, bituminous wood, corals, shells, crustaceans, and fish teeth are met with in it. Owing to its ready solubility, it is not found at the surface in moist climates. It has been formed by the evaporation of very saline water in enclosed basins—a process going on now in many salt-lakes (Great Salt Lake of Utah, Dead Sea), and on the surface of some deserts (Kirgis Steppe). In different parts of the world, deposits of salt have probably always been in progress from very early geological times. Saliferous formations of Tertiary and Secondary age are abundant in Europe, while in America they occur even in rocks as old as the Upper Silurian period, and among the Punjab Hills in still more ancient strata.[1]

Carnallite—a chloride of potassium and magnesium (p. 79). It occurs in a bed 20 to 30 metres thick which overlies the rock-salt in the saliferous series of Stassfurt, and has been found in other old salt deposits, as well as among the "salterns" or "salines" along the Mediterranean coast where the water of that inland sea is evaporated in the manufacture of salt. It so closely resembles rock-salt that it was formerly included with it, but it is much less frequently met with. It is a valuable source for the manufacture of potash-salts.

Limestone (Calcaire, Kalkstein),—essentially a mass of calcium-carbonate, sometimes nearly pure, and entirely or almost entirely soluble in hydrochloric acid, sometimes loaded with sand, clay, or other intermixture. Few rocks vary more in texture and composition. It may be a hard, close-grained mass, breaking with a splintery or conchoidal fracture; or a crystalline rock built up of fine crystalline grains of calcite, and resembling loaf-sugar in colour and texture; or a dull earthy friable chalk-like deposit; or a compact, massive, finely-granular rock resembling a close-grained sandstone or freestone. As its hardness is about 3, it can easily be scratched with a knife and the white powder gives a copious effervescence with acid. The specific gravity naturally varies according to the impurity of the rock, ranging from 2·5 to 2·8. The colours, too, vary extensively, the most common being shades of blue-grey and cream-colour passing into white. Some limestones are highly siliceous, the calcareous matter having been accompanied with silica in the act of deposition; others are argillaceous, sandy, ferruginous, dolomitic, or bituminous. By far the larger number of limestones are of organic origin; though owing to internal re-arrangement, their original clastic character has frequently been changed into a crystalline one. Under the present subdivision are placed all those limestones which have had a distinctly chemical origin, and also those which though doubtless, in many cases, originally formed of organic débris, have lost their fragmental, and have assumed instead a crystalline structure. (For the organic limestones see p.139.)

Compact, common limestone,—a fine-grained crystalline-granular aggregate. occurring in beds or laminæ interstratified with other aqueous deposits. When purest it is readily soluble in acid with effervescence, leaving little or no residue. Many varieties occur, to some of which separate names are given. *Hydraulic limestone* contains 10 per cent or more of silica (and usually alumina) and, when burnt and subsequently mixed with water, forms a cement or mortar, which has the property of "setting" or hardening under water. Limestones containing perhaps as much as 25 per cent of silica, alumina, iron, &c., that in themselves would be unsuitable for many of the ordinary purposes for which limestones are used, can be employed for making hydraulic mortar. These limestones occur in beds like those in the Lias of Lyme Regis, or in nodules like those of Sheppey, from which Roman cement is made. *Cementstone* is the name given to many pale dull ferruginous limestones, which contain an admixture of clay, and some of which can be profitably used for making hydraulic mortar or cement. *Fetid limestone* (*stinkstein, swinestone*) gives off a fetid smell (sulphuretted hydrogen gas), when struck with a hammer. In some cases, the rock seems to have been deposited by volcanic springs containing decomposable sulphides as well as lime. In other instances, the odour may be connected with the decomposition of imbedded organic matter. In some quarries in the Carboniferous Limestone of Ireland, as mentioned by Jukes, the freshly-broken rock may be smelt at a distance of a hundred yards when the men are at work, and occasionally the stench becomes so strong that the workmen are sickened by it, and require to leave off work for a time. *Cornstone* is an arenaceous or siliceous limestone particularly characteristic of some of the Palæozoic red sandstone formations. *Rottenstone* is a decomposed siliceous limestone from which most or all of the lime has been removed, leaving a siliceous skeleton of the rock. A similar decomposition takes place in some ferruginous limestones, with the result of leaving a yellow skeleton of ochre. Common limestone, having been deposited in water usually containing other substances in suspension or solution, is almost always mixed with impurities, and where the mixture is sufficiently distinct it receives a special name, such as siliceous limestone, sandy limestone, argillaceous limestone, bituminous limestone, dolomitic limestone.

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[1] On salt deposits of various ages, see A. C. Ramsay, *Brit. Assoc. Rep.* 1880, p. 10; also Index, *sub voc.* "Salt Deposits."

Travertine (calcareous tufa, calc-sinter) is the porous material deposited by calcareous springs, usually white or yellowish, varying in texture from a soft chalk-like or marly substance to a compact building-stone. (See Book III. Part II. Sect iii. §§ 3, 6.) *Stalactite* is the name given to the calcareous pendant deposit formed on the roofs of limestone-caverns, vaults, bridges, &c.; while the water, from which the hanging lime-icicles are derived, drips to the floor, and on further evaporation there, gives rise to the crust-like deposit known as *stalagmite*. Mr. Sorby has shown that in the calcareous deposits from fresh water there is a constant tendency towards the production of calcite crystals with the principal axis perpendicular to the surface of deposit. Where that surface is curved, there is a radiation or convergence of the fibre-like crystals, well seen in sections of stalactites and of some calcareous tufas (Fig. 108).

Oolite,—a limestone formed wholly or in part of more or less perfectly spherical grains, and having somewhat the aspect of fish-roe. Each grain consists of successive concentric shells of carbonate of lime, frequently with an internal radiating fibrous structure, which gives a black cross between crossed Nicols (Fig. 27). The calcareous material was deposited round some minute particle of sand or other foreign body which was kept in motion, so that all sides could in turn become encrusted. Oolitic grains of this character are now forming in the springs of Carlsbad (Sprudelstein); but they may no doubt also be produced where gentle currents in lakes, or in partially enclosed areas of the sea, keep grains of sand or fragments of shells drifting along in water, which is so charged with lime as to be ready to deposit it upon any suitable surface. An oolitic limestone may contain much impurity. Where the calcareous granules are cemented in a somewhat argillaceous matrix the rock is known in Germany as Rogenstein. Where the individual grains of an oolitic limestone are as large as peas, the rock is called a pisolite (pea-grit). The granules sometimes consist of aragonite. Oolitic structure is found in limestones of all ages from Palæozoic down to recent times.[1] Mr. E. Wethered has recently pointed out that many oolitic grains show curious vermiform twistings in their outer concentric coats, which he regards as of organic origin, either plant or animal (*Girvanella*).[1] In some instances oolites have had their calcareous matter replaced by carbonate or oxide of iron, so as to become oolitic ironstones.

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[1] Oolitic structure is found even among the limestones of the Dalradian metamorphic series of Scotland (Islay) which may possibly be pre-Palæozoic.

Marble (granular limestone),—a crystalline-granular aggregate composed of crystalline calcite-granules of remarkably uniform size, each of which has its own independent twin lamellæ (often giving interference colours) and cleavage lines. This characteristic structure is well displayed when a thin slice of ordinary statuary marble is placed under the microscope (Fig. 28). Typical marble is white, but the rock is also yellow, grey, blue, green, red, black, or streaked and mottled, as may be seen in the numerous kinds used for ornamental purposes. Its granular structure gives it a resemblance to loaf-sugar, whence the term "saccharoid" applied to it. Fine silvery scales of mica or talc may often be noticed even in the purest marble (*Cipolino*). Some crystalline lime-stones associated with gneiss and schist are peculiarly rich in minerals,—mica, garnet, tremolite, actinolite, anthophyllite, zoisite, vesuvianite, pyroxenes, and many other species occurring there often in great abundance. These inclusions can be isolated by dissolving the surrounding rock in acid (*ante*, p. 87).

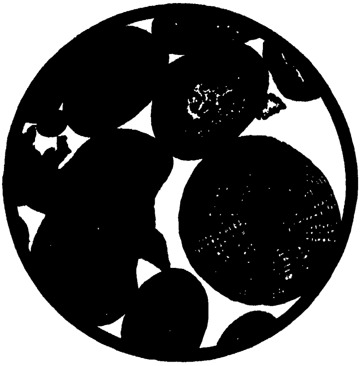

Fig. 27.—Microscopic Structure of Oolitic Limestone, after Sorby. (Magnified 30 Diameters.)

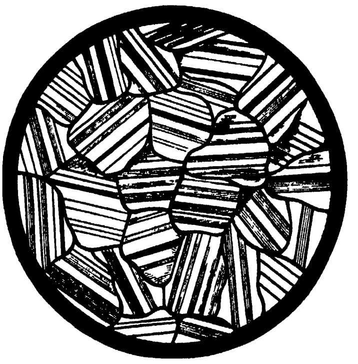

Fig. 28.—Microscopic Structure of white Statuary Marble. (Magnified 50 Diameters.)

Marble is regarded by most geologists as a metamorphic rock, that is, one in which the calcium-carbonate, whether derived from an organic or inorganic source, has been entirely recrystallized *in situ*. In the course of this change the original clay, sand or other impurities of the rock have been also crystallized, and now appear as the crystalline silicates just referred to. Marble occurs in beds and large lenticular masses associated with crystalline schists on many different geological horizons. In Canada it occurs of Laurentian ; in Scotland of Cambrian ; in Utah of Upper Carboniferous ; in Southern Europe of Triassic, Jurassic and Cretaceous age.

Dolomite (Magnesian Limestone) consists typically of a yellow or white, crystalline, massive aggregate of the mineral dolomite ; but the relative proportions of the calcium and magnesium-carbonates vary indefinitely, so that every gradation can be found, from pure limestone without magnesium-carbonate up to pure dolomite containing 45·65 per cent of that carbonate. Ferrous carbonate is also of common occurrence in this rock. The texture of dolomite is usually distinctly crystalline, the individual crystals being occasionally so loosely held together that the rock readily crumbles into a crystalline sand. A fissured cavernous structure apparently due to a process of contraction during the process of "*dolomitization*," is of common occurrence: even in compact varieties, cellular spaces occur, lined with crystallized dolomite (Rauchwacke), the crystals of which are often hollow and sometimes enclose a kernel of calcite. Other varieties are built up of spherical, botryoidal and irregularly-shaped concretionary masses. Dolomite, in its more typical forms, is distinguishable from limestone by its greater hardness (3·5–4·5) higher specific gravity (2·8–2·95), and much less easy solubility in acid. It occurs sometimes in beds of original deposit, associated with gypsum, rock-salt and other results of the evaporation of saturated saline waters; it is also found replacing what was once ordinary limestone. The process by which carbonate of lime is replaced by carbonate of magnesia, is referred to in Book III. Part I. Sect. iv. § 2.[1] Dolomite sometimes forms picturesque mountain masses, as in the Dolomite Mountains of the Eastern Alps.

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[1] *Geol. Mag.* 1889, p. 196 ; *Quart. Journ. Geol. Soc.* xlvi. (1890), p. 270. Mr. C. Reid has suggested that these tubular bodies may be due to the deposit of lime round organic filaments (*Algæ*) like the calcareous incrustation formed round fibres of hemp in kettles and boilers.

Gypsum—a fine granular to compact, sometimes fibrous or sparry aggregate of the mineral gypsum, having a hardness of only 1·5–2 (therefore scratched with the nail), and a specific gravity of about 2·32, and being unaffected by acids; hence readily distinguishable from limestone, which it occasionally resembles. It is normally white, but may be coloured grey or brown by an admixture of clay or bitumen, or yellow and red by being stained with iron-oxide. It occurs in beds, lenticular intercalations and strings, usually associated with beds of red clay, rock-salt, or anhydrite, in formations of many various geological periods from Silurian (New York) down to recent times. The Triassic gypsum deposits of Thuringia, Hanover and the Harz have long been famous. One of them runs along the south flank of the Harz Mountains as a great band six miles long and reaching a height of sometimes 430 feet.

Gypsum furnishes a good illustration of the many different ways in which some mineral substances can originate. Thus it may be produced, 1st, as a chemical precipitate from solution in water, as when sea-water is evaporated; 2nd, through the decomposition of sulphides and the action of the resultant sulphuric acid upon limestone; 3rd, through the mutual decomposition of carbonate of lime and sulphates of iron, copper, magnesia, &c.; 4th, through the hydration of anhydrite; 5th, through the action of the sulphurous vapours and solutions of volcanic orifices upon limestone and calcareous rocks.[2] It is in the first of these ways that the thick beds of gypsum associated with rock-salt in many geological formations have been formed. The first mineral to appear in the evaporation of sea-water being gypsum, it has been precipitated on the floors of inland seas and saline lakes before the more soluble salts.

Anhydrite,—the anhydrous variety of calcium-sulphate, occurs as a compact or granular, white, grey, bluish or reddish aggregate in saliferous deposits. It is less frequent than gypsum, from which it is distinguished by its much greater hardness (3–3·5) and into which it readily passes by taking up 0·2625 of its weight of water.[3] It often occurs in thin seams or partings in rock-salt; but it also forms large hill-like masses, of which the external parts have been converted into gypsum.

Ironstone.—Under this general term are included various iron-ores in which the peroxide, protoxide, carbonate, &c., are mingled with clay and other impurities. They have generally been deposited as chemical precipitates on the bottoms of lakes, under marshy ground, or within fissures and cavities of rocks. Some iron-ores are associated with schistose and massive rocks; others are found with sandstones, shales, limestones and coals; while some occur in the form of mineral veins. Those which have resulted from the co-operation of organic agencies are described at p. 146.

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[1] On the mineralogical nature of dolomite see O. Meyer, *Z. Deutsch. Geol. Ges.* xxxi. p. 445, Loretz, *op. cit.* xxx. p. 387, xxxi. p. 756. Renard, *Bull. Acad. Roy. Belg.* xlvii. (1879), No. 5.

[2] Roth. *Chem. Geol.* i. p. 553.

[3] See G. Rose on formation of this rock in presence of a solution of chloride of sodium. *Neues Jahrb. Min.* 1871, p. 932. Also Bischof, 'Chem. und Phys. Geol.' Suppl. (1871), p. 188.

Hæmatite (red iron-ore), a compact, fine-grained, earthy, or fibrous rock of a blood-red to brown-red colour, but where most crystalline, steel-grey and splendent, with a distinct cherry-red streak. Consists of anhydrous ferric oxide, but usually is mixed with clay, sand, or other ingredient, in such varying proportions as to pass, by insensible gradations, into ferruginous clays, sands, quartz, or jasper. Occurs as beds, huge concretionary masses, and veins traversing crystalline rocks; sometimes, as in Westmoreland, filling up cavernous spaces in limestone. Is found occasionally in beds of an oolitic structure among stratified formations. Some at least of the oolitic or pisolitic ironstones have resulted from the conversion of original grains of calcite in ordinary oolites into carbonate of iron which on oxidation has become magnetite, hæmatite, or limonite.

Limonite (brown iron-ore), an earthy or ochreous, compact, fine-grained or fibrous rock, of an ochre-yellow to a dark brown colour, distinguishable from hæmatite by being hydrous and giving a yellow streak. Occurs in beds and veins, sometimes as the result of the oxidation of ferrous carbonate; abundant on the floors of some lakes; commonly found under marshy soil where it forms a hard brown crust upon the impervious subsoil (*bog-iron-ore*). Found likewise in oolitic concretions sometimes as large as walnuts, consisting of concentric layers of impure limonite with sand and clay (*Bohnerz*). (See p. 146 and Book III. Part II. Sect. iii. § 3.)

Spathic Iron-ore, a coarse or fine crystalline or dull compact aggregate of the mineral siderite or ferrous carbonate, usually with carbonates of calcium, manganese and magnesium; has a prevalent yellowish or brownish colour, and when fresh, its rhombohedral cleavage-faces show a pearly lustre, which soon disappears as the surface is oxidized into limonite or hæmatite. Occurs in beds and veins, especially among older geological formations. The colossal Erzberg at Eisenerz in Styria, which rises more than 2700 feet above the valley, consists almost wholly of siderite.[1]

Clay-ironstone (Sphærosiderite), a dull brown or black, compact form of siderite, with a variable mixture of clay, and usually also of organic matter. Occurs in the Carboniferous and other formations, in the form either of nodules, where it has usually been deposited round some organic centre, or of beds interstratified with shales and coals. It is more properly described at p. 147, with the organically derived rocks.

Magnetic iron-ore, a granular to compact aggregate of magnetite, of a black colour and streak, more or less perfect metallic lustre, and strong magnetism. Commonly contains admixtures of other minerals, notably of hæmatite, chrome-iron, titanic-iron, pyrites, chlorite, quartz, hornblende, garnet, epidote, felspar. Occurs in beds and enormous lenticular masses (Stöcke) among crystalline schists, likewise in segregation-veins of gabbros and other eruptive rocks; also occasionally in an oolitic form (probably as a pseudomorph after an original calcareous oolite) among Palæozoic rocks, as in the so-called "pisolitic iron-ore" of North Wales. Among the Scandinavian gneisses lies the iron mountain of Gellivara in Lulea-Lappmark, 17,000 feet long, 8500 feet broad, and 525 feet high.

Siliceous Sinter (Geyserite, Kieselsinter), the siliceous deposit made by hot springs, including varieties that are crumbling and earthy, compact and flinty, finely laminated and shaly, sometimes dull and opaque, sometimes translucent, with pearly or waxy lustre, and with chalcedonic alterations in the older parts. The deposit may occur as an incrustation round the orifices of eruption, rising into dome-shaped, botryoidal, coralloid, or columnar elevations, or investing leaves and stems of plants, shells, insects, &c., or hanging in pendant stalactites from cavernous spaces which are from time to time reached by the hot water. When purest, it is of snowy whiteness, but is often tinted yellow or flesh colour. It consists of silica 84 to 91 per cent, with small proportions of alumina, ferric oxide, lime, magnesia, and alkali, and from 5 to 8 per cent of water. (See Book III. Part II. Sect. iii. § 3, par. 6.)

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[1] Zirkel, *Lehrb.* i. p. 345.

Flint and Chert have been already described among the rocks of organic origin (*ante*, p. 141). **Hornstone**, an excessively compact siliceous rock, usually of some dull dark tint, occurs in nodular masses or irregular bands and veins. The name has sometimes been applied to fine flinty forms of felsite. **Vein-Quartz** may be alluded to here as a substance which sometimes occurs in large masses. It is a massive form of quartz found filling veins (sometimes many yards broad) in crystalline and clastic rocks; more especially in metamorphic areas. (See Quartz Rocks, p. 179.)

Some of the other varieties of silica occurring in large masses may be classed as rocks. Such are Jasper, and Ferruginous Quartz. These, as well as common vein-quartz, occur as veins traversing both stratified and unstratified rocks; also as beds associated with the crystalline schists. With them may be grouped Lydian-Stone (*Lydite*, *Kieselschiefer*), a black or dark-coloured, excessively compact, hard, infusible rock with splintery fracture, occurring in thin, sharply defined bands, split by cross joints into polygonal fragments, which are sometimes cemented by fine layers of quartz. It consists of an intimate mixture of silica with alumina, carbonaceous materials, and oxide of iron, and under the microscope shows minute quartz-granules with dark amorphous matter. It occurs in thin layers or bands in the Silurian and later Palæozoic formations interstratified with ordinary sandy and argillaceous strata. As these rocks have not been materially altered, the bands of Lydian-stone may be of original formation, though the extent to which they are often veined with quartz shows that they have, in many cases, been permeated by siliceous water since their deposit. The siliceous rocks due to the operations of plant and animal life are described on p. 141, also in Book III. Part II. Sect. iii. § 3.

Some originally clastic siliceous rocks have acquired a more or less crystalline structure from the action of thermal water or otherwise. One of the most marked varieties has been termed *Crystallized Sandstone* (see p. 132). Another variety, known as *Quartzite*, is a granular and compact aggregate of quartz, which will be described in connection with the schistose rocks among which it generally occurs (p. 180).

II. MASSIVE—ERUPTIVE—IGNEOUS.

Almost all the members of this important sub-division have been produced from within the crust of the earth, in a molten condition. Nearly all consist of two or more minerals. Considered from a chemical point of view, they may be described as mixtures, in different proportions, of silicates of alumina, magnesia, lime, potash, and soda, usually with magnetic iron and phosphate of lime. In one series, the silicic acid has not been more than enough to combine with the different bases; in another, it occurs in excess as free quartz. Taking this feature as a basis of arrangement, some petrographers have proposed to divide the rocks into an acid group, including such rocks as granite, quartz-porphyry and rhyolite, where the percentage of silica ranges from 60 to 75 or more, a basic group, typified by such rocks as basalt, where the proportion of silica is only about 50 per cent or less, and an intermediate group represented by the andesites with a proportion of silica ranging between that of the other two groups.[1]

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[1] See a paper on the chemical relations of the eruptive rocks by Prof. Rosenbusch, *Tschermak's Min. Mittheil.* xi. (1889), p. 144, also the paper quoted in footnote (2) on p. 156, and a Memoir on "the origin of Igneous Rocks," by J. P. Iddings, *Phil. Soc. Washington*, 1892, p. 90.

In the vast majority of igneous rocks, the chief silicate is a felspar—the number of rocks where the felspar is represented by another silicate (as leucite or nepheline) being comparatively few and unimportant. As the felspars group themselves into two divisions, the monoclinic or orthoclase, and the triclinic or plagioclase, the former with, on the whole, a preponderance of silica; and as these minerals occur under tolerably distinct and definite conditions, other petrographers divide the felspar-bearing Massive rocks into two series: (1) the Orthoclase rocks, having orthoclase as their chief silicate, and often with free silica in excess, and (2) the Plagioclase rocks, where the chief silicate is some species of triclinic felspar. The former series corresponds generally to the acid group above mentioned, while the plagioclase rocks are intermediate and basic. It has been objected to this arrangement that the so-called plagioclase felspars are in reality very distinct minerals, with proportions of silica, ranging from 43 to 69 per cent; soda from 0 to 12; and lime from 0 to 20.[1] In addition to the felspar-rocks, there must be noted those in which felspar is either wholly absent or sparingly present, and where the chief part in rock-making has been taken by nepheline, leucite, olivine, or serpentine.

From the point of view of internal structure, a classification based upon microscopic research has been adopted by other writers, who recognise three leading types of micro-structure—*Granular*, *Porphyritic* and *Glassy*, or *Holocrystalline*, *Hemicrystalline* and *Vitreous*. MM. Fouqué and Michel-Lévy, pointing out that most eruptive rocks are the result of successive stages of crystallization, each recognisable by its own characters, show that two phases of consolidation are specially to be observed, the first (porphyritic) marked by the formation of large crystals (phenocrysts) which were often broken and corroded by mechanical and chemical action within the still unsolidified magma; the second by the formation of smaller crystals, crystallites, &c., which are moulded round the older series. In some rocks the former, in others the latter of these two phases is alone present. Two leading types of structure are recognised by these authors among the eruptive rocks. 1. Granitoid, where the constituents are mainly those of the second epoch of consolidation, but where neither amorphous magma, nor crystallites are to be seen. This structure includes three varieties, (*a*) the *granitoid* proper, having crystals of approximately equal size; (*b*) *pegmatoid*, where there has been a simultaneous crystallization and regular arrangement of two constituents; (*c*) *ophitic*, in which the felspars are ranged parallel to one of their crystalline faces, forming a kind of transition into microlitic rocks. 2. Trachytoid, distinguished by a more marked contrast between the crystals of the first and second consolidation, the usual presence of an amorphous magma, and the fluxion structure. Three varieties are named: (*a*) *petrosiliceous*, with trains and spherulites of a finely clouded substance characteristic of the more acid rocks; (*b*) *microlitic*, characterised by the abundance of microlites of felspars and other minerals; (*c*) *vitreous*, derived from the two foregoing varieties by the predominance of the amorphous paste.[1]

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[1] Dana, *Amer. Journ. Sci.* 1878, p. 432. The modern methods of separating the felspars remove some of the difficulty above referred to.

It is common to introduce a chronological element into the classification of the massive rocks and to divide them into an ancient (Palæozoic and Mesozoic) and modern (Tertiary and recent) series. Certain broad distinctions can doubtless be made between many ancient and modern eruptive rocks; but, for reasons already stated, it seems inexpedient, in the present state of our knowledge, to employ relative antiquity (which must be determined by a totally distinct branch of geological inquiry, and may be erroneously determined) as a basis of petrographical arrangement.[2]

In the following arrangement the three-fold division first mentioned above is adopted, according to the relative abundance of silica: 1st Acid, 2nd Intermediate, 3rd Basic. In each of these series there is a range of structure from completely crystalline to completely glassy. The holocrystalline rocks are as a rule the deep-seated representatives of each series, while the vitreous and semi-vitreous are those which have either been erupted to the surface or have been connected with volcanic rather than plutonic action. No system of classification yet proposed can avoid incongruities, and it must be remembered that the hard and fast lines of our nomenclature do not represent any really abrupt demarcations in nature. As one rock graduates into another, our terminology should be elastic, so as to include such transitional forms.

i. Acid Series.

In this family the silicic acid has been in such excess as often to separate out in the form of free quartz. Sometimes, as in granite, it has not assumed a definitely crystallized form, but is moulded round the other crystals as a later stage of consolidation. In other rocks (quartz-porphyry, &c.) it occurs as a product of earlier consolidation, and often assumes perfect crystallographic contours, occurring even in double pyramids. The texture of the rocks is (1) holocrystalline or crystalline-granular (granitoid) as typically developed in granite; (2) hemi-crystalline (porphyritic, trachytoid), as in quartz-porphyry or felsite; (3) vitreous, as in obsidian.

Granite.[3]—A thoroughly crystalline-granular admixture of quartz, felspar, and mica, in particles of tolerably uniform size (Figs. 15 and 29). The felspar is chiefly white or pink orthoclase, but triclinic felspars (oligoclase and albite) may often be observed in smaller quantity, frequently distinguishable by their fine striation and more waxy lustre. Microcline is not infrequent, as well as the intercrystallization of orthoclase and plagioclase (Perthite). The mica may be the potash (muscovite) variety, usually of a white silvery aspect, but more commonly biotite or other dark brown or black variety. The quartz may be observed to form a kind of paste or magma wrapping round the other ingredients. Only in cavities of the granite do the component minerals occur in independent well-formed crystals, and there too the accessory minerals (beryl, topaz, tourmaline, garnet, &c.) are chiefly found.

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[1] 'Minéralogie Micrographique,' p. 150.

[2] For a tabular arrangement of the massive (eruptive) rocks and critical remarks on their classification, see Rosenbusch, *Neues Jahrb.* 1882, ii. p. 1.

[3] On the structure of granite, see the manuals of Zirkel and Rosenbusch and the memoirs there cited; also Zirkel's 'Microscop. Petrography,' 1876, p. 39; Phillips, *Q. J. Geol. Soc.* xxxi. p. 330; xxxvi. p. 1. J. C. Ward, *op. cit.* p. 569; and xxxii. p. 1. King's 'Systematic Geology' (vol. i. of *Explor. 40th Parallel*), p. 111 *et seq.* Michel-Lévy, *Bull. Soc. Géol. France*, 3rd ser. iii. p. 199. Rosenbusch, *Zeitsch. Deutsch. Geol. Gesell.* xxviii. (1876), p. 369. H. Möhl, *Nyt. Mag. Nat.* xxiii. p. 1 *et seq.* J. Lehmann, 'Untersuchungen über die Entstehung der Altkrystallinischen Schiefergesteine,' 1884, p. 3. W. J. Sollas, *Trans. Roy. Irish Acad.* xxix. Part xiv. (1891).

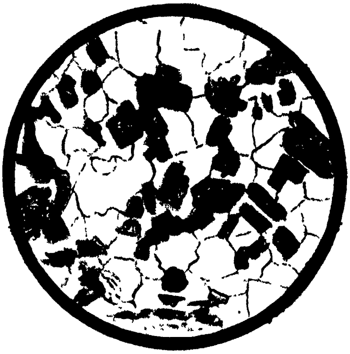

Fig. 29.—Holocrystalline Structure of Granite (magnified).

From a microscopic examination of granite, it was formerly inferred that the rock has a thoroughly crystalline structure, with no megascopic ground-mass, nor microscopic base of any kind between the crystals or crystalline individuals. More recent and exhaustive study of the subject, however, has led to the conclusion that though nothing like a vitreous, or even porphyritic, ground-mass can be detected, there is yet sometimes discernible an analogous kind of entirely crystalline magma, in which the crystals or crystalline débris of the rock are embedded, and in which they are partially dissolved. Having regard to the relations between this magma and its enclosed minerals, M. Michel-Lévy has observed that microscopic examination points to a distinction between granites in which the quartz is more recent than the other constituents and has consolidated at once, and those in which there are remains of earlier bi-pyramidal quartz. He distinguishes these two series as (A) Ancient granites, composed of black mica, hornblende, oligoclase, and orthoclase, forming a crystalline débris embedded in a more recent crystalline magma of orthoclase and quartz. (B) Porphyroid granites, generally finer in grain than the preceding, and further distinguished by the occurrence of bi-pyramidal crystals of quartz (which made their appearance between the old felspar and the recent orthoclase), and of a notable quantity of white mica (rare among the ancient granites) posterior in advent even to the more recent quartz.[1]

Among the component minerals of granite, the quartz presents special interest under the microscope. It is often found to be full of cavities containing liquid, sometimes in such numbers as to amount to a thousand millions in a cubic inch and to give a milky turbid aspect to the mineral. The liquid in these cavities appears usually to be water containing sodium and potassium chlorides, with sulphates of these metals and of calcium (p. 110).

The mean of eleven analyses of granites made by Dr. Haughton gave the following average composition: silica, 72·07; alumina, 14·81; peroxide of iron, 2·22; potash, 5·11; soda, 2·79; lime, 1·63; magnesia, 0·33; loss by ignition, 1·09; total, 100·05, with a mean specific gravity of 2·66.

Most large masses of granite present differences of texture in different parts of their area. Some of these variations depend on the relation of the mass to the surrounding rocks (see *postea*, p. 565). Others may occur in any portion of a granite boss, and have been produced by the circumstances in which the mass consolidated. Some granites are marked by the occurrence of the cavities above referred to where the individual minerals have had room to assume sharply defined crystalline forms. Many granites are apt to be traversed by veins, sometimes due to a segregation of the surrounding minerals in rents of the original pasty magma, sometimes to a protrusion of a less coarsely crystalline (micro-granitic, felsitic) material into the main rock (Fig. 30). Some of the more important of these varieties are distinguished by special names.

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[1] *Bull. Soc. Géol. France*, 3rd ser. iii. (1875), p. 199.

Thus, where the component quartz and felspar have crystallized together so as to enclose each other and assume a tendency to an orientation of their longer axes in one general direction, as they are specially apt to do in segregation-veins, the rock is termed Pegmatite.[1] One of the most interesting structural varieties is the form of pegmatite termed Graphic Granite, in which the orientation of the quartz and felspar is singularly well developed (Fig. 31). The quartz has assumed the shape of long imperfect columnar shells, placed parallel to each other and enclosed within the orthoclase, so that a transverse section bears some resemblance to Hebrew writing. The two minerals have crystallized together, with their principal axes parallel. This intergrowth seems to show that there could have been little or no internal movement of the veins, in which it so frequently occurs, when the component minerals assumed their crystalline forms. Where the intergrowth is on a minute scale it is known as micropegmatite, and it forms the base of the rock to which the name of Granophyre has been given (Fig. 5). Here and there, an example may be found of a granite becoming fine-grained, but containing large scattered felspar crystals. Such a rock may be termed a *porphyritic granite.* Some granites abound in enclosed crystalline concretions or

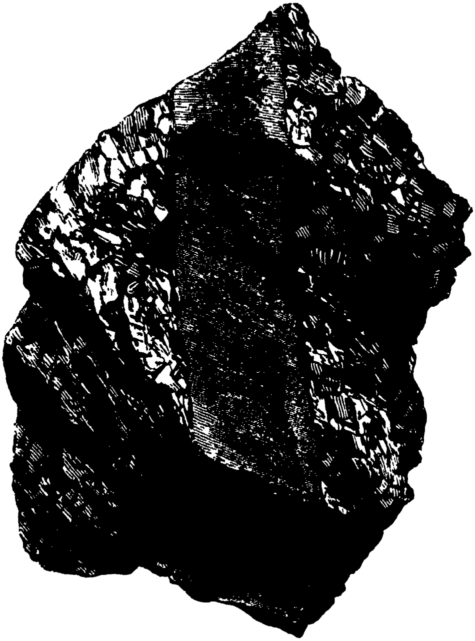

Fig. 30.—Vein of finer grain (aplite) traversing a coarsely crystalline Granite.

Fig. 31.—Graphic Granite (nat. size).

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[1] For an admirable and exhaustive account of the Pegmatite veins, and their associated minerals in Southern Norway, see the great monograph by Prof. W. C. Brögger in Groth's *Zeitsch. Krystallographie,* xvi. (1890).

fragments. These are sometimes mere segregations of the materials of the granite, when they are usually ovoid in form and porphyritic in structure; in other cases, they are fragments of other rocks, and are then commonly schistose in structure and irregular in form.[1] In rare examples the component minerals of granite have crystallized with a radial concentric arrangement into rounded ball-like aggregates (spheroidal, orbicular granite).[2] In the centre, as well as round the edges of large bosses of granite, the minerals occasionally assume a more or less perfectly schistose arrangement. When this takes place, the rock is called gneissose or gneiss granite. (See Book IV. Part VII.)

Differences in the proportions or nature of the component minerals have likewise suggested distinctive names. Of these the following are the more important: **Granitite**, (biotite granite)—a mixture of pink orthoclase and abundant oligoclase, with a little quartz, some blackish green magnesia-mica, and occasionally with hornblende or augite. **Hornblende-granite**—a rock with hornblende added to the other normal constituents of granite, and usually poorer in quartz than normal granite. A well-known variety occurs at Syene in Upper Egypt, whence it was obtained anciently in large blocks for obelisks and other architectural works. The well-known Egyptian monoliths are made of it. It was called by Pliny "Syenite,"—a name adopted by Werner as a general designation for hornblendic granites without quartz. The rock of Syene is really a hornblende-biotite-granite. **Augite-granite**—a variety in which augite occurs with black mica. **Tourmaline granite**—a granitite with disseminated tourmaline. **Greisen**—a rare granitic rock from which the felspar has disappeared, found in some granite districts, especially in those wherein mineral-veins occur. **Aplite**—a fine-grained mixture of quartz and felspar, which have not infrequently intergrown (micropegmatite); found especially in veins in granite. "Elvan" is a Cornish term for a crystalline-granular mixture of quartz and orthoclase, forming veins which proceed from granite, or occur only in its neighbourhood, and are evidently associated with it.[3] Under the name *Granulite* M. Michel-Lévy includes certain fine-grained granites with white mica, which to the naked eye appear to be composed entirely of felspar and quartz, or of felspar alone, though both mica and quartz appear in abundance when the rocks are microscopically examined. He includes in this category most of the rocks of the Alps described as "protogine."

Surrounding large masses of granite there are usually numerous veins, which consist of granite, quartz-porphyry, felsite, or sometimes even spherulitic material (Mull). There can be no doubt that these finer-grained protrusions really proceed from the crystalline granite mass. Lossen has shown that the Bode vein in the Harz has a granitoid centre, with compact porphyry sides, in which he found with the microscope a true glassy base.[4] Sometimes the rocks associated in this way with granite differ in composition from the main granite. Tourmaline is one of the characteristic minerals of granite-veins, though less observable in the main body of the rock; with quartz, it forms **Schorl-rock**.

Granite weathers chiefly by the decay of its felspars. These are converted into kaolin, the mica becomes yellow and soft, while the quartz stands out scarcely affected. The granite of the south-west of England has weathered to a depth of 50 feet and upwards, so that it can be dug out with a spade, and is largely used as a source of porcelain-clay.

Granite occurs (1) as an eruptive rock, forming huge bosses, which rise through other formations both stratified and unstratified, and sending out veins into the surrounding and overlying rocks, which usually show evidence of much alteration as they approach of the typical structures of rhyolite can be detected in felsites. The ground-mass of these rocks has given rise to much discussion, but it is now generally recognised as a more or less altered condition of the devitrification of an original vitreous mass (p. 117). Secondary changes have in large measure destroyed the original microlitic structure, but traces of it can often be found while the spherulitic and perlitic forms frequently remain almost as fresh as in a recent rock. Felsites with a large proportion of alkalies, especially soda, have been called *Keratophyres.*[1]

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[1] J. A. Phillips, *Q. J. Geol. Soc.* xxxvi. (1880), p. 1.

[2] W. C. Brogger and H. Backstrom, *Geol. Stockholm Förhandl.* ix. (1887), p. 307. Hatch, *Quart. Journ. Geol. Soc.* xliv. (1888), p. 548, and authorities there cited.

[3] J. A. Phillips, *Q. J. Geol. Soc.* xxxi. p. 334. Michel-Lévy, *Bull. Soc. Géol. France*, iii. 3rd ser. p. 201.

[4] *Zeitsch. Deutsch. Geol. Ges.* xxvi. (1874), p. 856.

Felsites have been found abundantly as interbedded lavas with tuffs and agglomerates associated with Silurian and older rocks in Wales and Shropshire.[2] Soda-felsites or keratophyres have been found to play a considerable part among the materials erupted by the Lower Silurian volcanoes of the south-east of Ireland.[3]

The **vitreous acid rocks** form an interesting group in which we may still detect what was probably the original condition of at least the rhyolites and felsites. Every gradation can be traced from a perfect glass into a thoroughly devitrified and even crystalline rock. As already remarked, the original vitreous condition of rhyolite can still be seen even with the naked eye in the clots and streaks of glass that occasionally run through it in the direction of its flow-structure. Various names have been given to the glassy rocks, of which the chief are obsidian, pitchstone and pumice. These, however, are not to be regarded as distinct rock-species but rather as the glassy condition of different lavas.

Obsidian (rhyolite-glass)—the most perfect form of volcanic glass, externally resembling bottle glass, having a perfect conchoidal fracture, and breaking into sharp splinters, transparent at the edges. Its colours are black, brown, or greyish-green, rarely yellow, blue, or red, but not infrequently streaked or banded with paler and darker hues. A thin slice of obsidian prepared for the microscope is found to be very pale yellow, brown, grey, or nearly colourless, and on being magnified shows that the usual dark colours are almost always produced by the presence of minute opaque crystallites, which present themselves as black opaque trichites, sometimes beautifully arranged in eddy-like lines showing the original fluid movement of the rock (Fig. 19); also as rod-like transparent microlites. They occasionally so increase in abundance as to make the rock lose the aspect of a glass and assume that of a dull flint-like or enamel-like stone. This devitrification can only be properly studied with the microscope. Again, dull grey enamel-like spherulites appear in some parts of the rock in great abundance, drawn out into layers so as to give the rock a fissile structure, while steam- or gas-cavities likewise occur, sometimes so large and abundant as to impart a cellular aspect. The occurrence of abundant sanidine crystals gives rise to *Porphyritic Obsidian.* Many obsidians, from the increase in the number of their steam-vesicles, pass into pumice. Now and then, the steam-pores are found in enormous numbers, of extremely minute size, as in an obsidian from Iceland, a plane of which, about one square millimetre in size, has been estimated to include 800,000 pores. The average chemical composition of obsidian is—silica, 71·0; alumina, 13·8; potash, 4·0; soda, 5·2; lime, 1·1; magnesia, 0·6; oxides of iron and manganese, 3·7; loss, 0·6 (little or no water). Mean specific gravity, 2·40. Obsidian occurs as a product of the volcanoes of late geological periods. It is found in Lipari, Iceland, and Teneriffe; in North America, it has been erupted from many points among the Western Territories;[1] it is met with also in New Zealand.

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[1] Gumbel, 'Palaeolit. Eruptivgest. Fichtelgebirg.' (1874), p. 43. Rosenbusch, 'Mikroskop. Physiog.' ii. 434.

[2] Mr. Allport described some ancient forms of perlitic structure from Shropshire, in what were probably once ordinary rhyolites, *Q. J. Geol. Soc.* xxxiii. p. 449; and Mr. Rutley showed the presence of the same structure among the Lower Silurian lavas of North Wales. *Op. cit.* xxxv. p. 508.

[3] F. H. Hatch, *Mem. Geol. Surv. Ireland, Explanation of Sheet* 130; *Geol. Mag.* 1889, p. 70.

Pitchstone is a name given to the less perfectly glassy acid rocks, which are distinguished by a resinous or pitch-like lustre, and internally by a more advanced development of microlites than in obsidian. They thus represent a further stage of devitrification. These rocks are easily frangible, breaking with a somewhat splintery fracture, translucent on thin edges, with usually a black or dark green colour, that ranges through shades of green, brown, and yellow to nearly white. Examined microscopically, they are found to consist of glass in which are diffused hair-like, feathery and rod-shaped microlites, or more definitely formed crystals of orthoclase, plagioclase, quartz, hornblende, augite, magnetite, &c. The pitchstone of Corriegills, in the island of Arran, presents abundant green, feathery, and dendritic microlites of hornblende (Fig. 14).[2] Occasionally, as in Arran, pitchstone assumes a spherulitic or perlitic structure. Sometimes it becomes porphyritic, by the development of abundant sanidine crystals (Isle of Eigg).

Pitchstone is found as (1) intrusive dykes, veins, or bosses, probably in close connection with former volcanic activity, as in the case of the dykes, which in Arran traverse Lower Carboniferous rocks, but are probably of Miocene age, and those which in Meissen send veins through and overspread the younger Palæozoic felsite-porphyries; (2) sheets which have flowed at the surface, as in the remarkable mass forming the Scuir of Eigg, which has filled up a river-channel of older Tertiary age.[3]

Pumice (Ponce, Bimstein)—a general term for the loose, spongy, cellular, filamentous or froth-like parts of lavas. So distinctive is this structure, that the term *pumiceous* has come into general use to describe it. There can be no doubt that this froth-like rock owes its peculiarity to the abundant escape of steam or gas through its mass while still in a state of fusion. The most perfect forms of pumice are found among the acid lavas, but this type of rock may be met with in the other groups. Microscopic examination of a rhyolitic pumice reveals a glass crowded with enormous numbers of minute gas- or vapour-cavities, usually drawn out in one direction, also abundant crystallites like those of obsidian. Owing to its porous nature, pumice possesses great buoyancy and readily floats on water, drifting on the ocean to distances of many hundreds of miles from land, until the cells are gradually filled with water, when the floating masses sink to the bottom.[4] Abundant rounded blocks of pumice were dredged up by the *Challenger* from the floor of the Atlantic and Pacific Oceans.

ii. Intermediate Series.

In this series, the average percentage of silica is considerably less than in the acid series (56-66 per cent). Free quartz is not found as a marked constituent, although occasionally it occurs in some quantity, as microscopic examination has shown in the case even of some rocks where the mineral was formerly believed to be absent. A range of structure is displayed similar to that in the acid series. The thoroughly crystalline varieties are typified by syenite (and diorite), representing the granites of the acid rocks, those which possess a porphyritic ground-mass by orthoclase-porphyry, trachyte, and andesite, answering to quartz-porphyry and rhyolite, while the vitreous condition is represented among the trachytes and andesites by dark glasses of the obsidian and pitchstone types.

Syenite.—This name, formerly given in England to a granite with hornblende replacing mica, is now restricted to a rock consisting essentially of a holocrystalline mixture of orthoclase and hornblende, to which plagioclase, biotite, augite, magnetite, or quartz may be added. As already mentioned, the word, first used by Pliny in reference to the rock of Syene, was introduced by Werner as a scientific designation. It was applied by him to the rock of the Plauenscher-Grund, Dresden; he afterwards, however, made that rock a greenstone. The base of all syenites, like that of granites, is thoroughly crystalline, without an amorphous ground-mass. The typical syenite of the Plauenscher-Grund, formerly described as a coarse-grained mixture of flesh-coloured orthoclase and black hornblende, containing no quartz, and with no indication of plagioclase, was regarded as a normal orthoclase-hornblende rock. Microscopical research has, however, shown that well-striated triclinic felspars, as well as quartz, occur in it. Its composition is:—silica, 59·83; alumina, 16·85; protoxide of iron, 7·01; lime, 4·43; magnesia, 2·61; potash, 6·57; soda, 2·44; water, etc., 1·29; total, 101·03. Average specific gravity, 2·75 to 2·90.

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[1] For an account of the obsidian of the Yellowstone Park see J. P. Iddings, *7th Rept. U. S. Geol. Surv.* (1885-86), p. 255; consult also Zirkel, 'Microscop. Petrog.'

[2] See F. A. Gooch, *Min. Mittheil.* 1876, p. 185. Allport, *Geol. Mag.* 1881, p. 438.

[3] *Quart. Journ. Geol. Soc.* (1871), p. 303.

[4] On porosity, hydration, and flotation of pumice, see Bischof, 'Chem. und Phys. Geol.' suppl. (1871), p. 177.

Syenite is of much less frequent occurrence than granite. While always thoroughly granitic in structure, it varies in texture from coarse granular, where the individual minerals can readily be distinguished by the naked eye, to compact. Among its accessory minerals of common occurrence may be mentioned titanite (sphene), quartz, apatite, epidote, orthite, magnetite, pyrite, zircon. The predominance of one or more of the ingredients has given rise to the separation of a few varieties under distinctive names. In the typical syenite, the dark silicate is almost wholly hornblende; sometimes there are to be found traces of augite within the hornblende, indicating that the former mineral was the original constituent and has been changed by paramorphism. Where the ferro-magnesian silicate is mainly augite, as in the well-known rock of Monzoni, the rock is termed Augite-syenite or Monzonite; where brown mica predominates it gives rise to Mica-syenite or Minette.

Elaeolite-syenite (*Nepheline-syenite*) is a granitoid rock, characterised by the association of the variety of nepheline known as elaeolite with orthoclase, and with minor proportions of plagioclase, microcline, hornblende, augite, biotite, sodalite, zircon, and sphene. It is distinguished by the rare minerals, upwards of fifty in number, which it contains, and in which some of the rarer elements are combined, such as thorium, yttrium, cerium, lanthanum, tantalum, niobium, zirconium, &c. It is typically developed in Southern Norway (Brevig, Laurvig). Where zircon enters as an abundant constituent the rock is known as Zircon-syenite. Foyaite is the name given to a hornblendic variety found at Mount Foya, Portugal; Miascite is a variety with abundant mica, found at Miask; Ditroite, containing sodalite, spinel, etc., occurs at Ditró in Transylvania.

Orthoclase-Porphyry (Micro-syenite, Quartzless-porphyry, Orthophyre) stands to the syenites in the same relation that quartz-porphyry or micro-granite does to the granites. It is composed of a compact micro-granitic ground-mass, with little or no free quartz, but through which are usually scattered numerous crystals of orthoclase, sometimes also a triclinic felspar, black hornblende and glancing scales of dark biotite. It contains from 55 to 65 per cent of silica, thus differing from quartz-porphyry and felsite in its smaller proportion of this acid. It is also rather more easily scratched with the knife, but except by chemical or microscopical analysis, it is often impossible to draw a distinction between this rock and its equivalents in the acid series.

Orthoclase-porphyry occurs in veins, dykes, and intrusive sheets. Probably many so-called "felstones," whether occurring as lavas or as intrusive masses among the older Palæozoic formations, are really orthoclase-porphyries. Some highly micaceous varieties have been called Mica-trap—a vague term under which have also been included Minettes, Micaceous Quartz-porphyries, &c. The name Lamprophyre, originally given by Gümbel to some mica-traps from the Fichtelgebirge, has been proposed by Rosenbusch as a general term for the Mica-traps, divisible into two groups—the Orthoclastic, or syenitic, where the felspar is orthoclase (Minettes), and the Plagioclastic or dioritic, where the felspar is a plagioclase variety (Kersantites).[1] The lamprophyres occur abundantly as dykes or veins of a fine-grained texture, and dull reddish to brownish colour, among the older Palæozoic rocks of Britain.[2]

The orthoclase-porphyry of Pieve in the Vicentin was found by Von Lasaulx to have the following composition:—silica, 61·07; alumina, 18·56; peroxides of iron and manganese, 2·60; potash, 6·83; soda, 3·18; lime, 2·86; magnesia, 1·18; carbonic acid, 1·36; loss, 2·13—specific gravity, 2·59.[3]

Diorite.[4]—Under this name is comprehended a group of rocks, which, possessing a granitic structure, differ from the granites in their much smaller percentage of silica, and from the syenites in containing plagioclase instead of orthoclase as their chief constituent. They are sometimes divided into two sections, the quartz-diorites and the normal diorites. Many of these rocks were formerly included in the general division of "Greenstones."

Quartz-diorite—a holocrystalline mixture of plagioclase (oligoclase, less frequently labradorite) and quartz with some hornblende, augite, or mica. It outwardly resembles grey granite, and, indeed, includes many so-called granites. Its silica ranges up to 67 per cent. In normal Diorite, quartz is almost entirely absent; hornblende and black mica occur together in some varieties, while pyroxene characterises others. Under the microscope a thoroughly crystalline structure is seen, and among the pyroxene-diorites the felspar and pyroxene are sometimes intergrown in ophitic aggregates. The average chemical composition of quartzless diorite is: silica, 54; alumina, 16–18; potash, 1·5–2·5; soda, 2–3; lime, 6–7·5; magnesia, 6·0; oxides of iron and manganese, 10–14; mean specific gravity, about 2·95.

Among the varieties of diorite, the following may be mentioned. Corsite (from Corsica)—a granitoid mixture of greyish-white plagioclase, blackish-green hornblende, and some quartz, which have grouped themselves into globular aggregations with an internal radial and concentric structure (Orbicular diorite, Kugeldiorit, Napoleonite—Fig. 8). Tonalite (from Monte Tonale, Tyrol)—a variety containing quartz, hornblende, and biotite in strongly contrasted colours. Epidiorite—a name given to ancient rocks which have originally been pyroxenic eruptive masses, but, by metamorphism, have acquired a crystalline re-arrangement of their constituents, the pyroxene being changed into hornblende, often fibrous or actinolitic, the felspar becoming granular, and the whole rock having acquired a more or less distinct schistose structure. The dark intrusive sheets associated with the crystalline schists of the Scottish Highlands and the north of Ireland are largely epidiorites. Some of these rocks are quartziferous, but many of them belong to the basic series (see p. 627).

As the granites pass into fine grained quartz-porphyries, and the syenites into compact orthoclase-porphyries, so the diorites have their close-textured varieties, which are comprised under the general term Aphanite, divisible into *Quartz-aphanite* and *Normal aphanite*. The general characteristic of these rocks is that the constituent minerals become so minute as to disappear from the naked eye. They are dark heavy close-grained masses. They merge into the basic diabases (p. 170).

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[1] The typical locality for these rocks is Kersanton in Brittany, where they are dark-green and remarkably durable. A singular vein of kersantite, 3 to 6½ feet broad, has been traced for nearly five miles in the Harz. Lossen, *Zeitsch. Deutsch. Geol. Ges.* xxxii. (1880), p. 445. *Jahrb. Preuss. Geol. Landesanst.* 1880. A. von Groddeck, *op. cit.* 1882. M. Koch, *op. cit.* 1886. Barrois, *Assoc. Française* (1880), p. 561; *Ann. Soc. Géol. Nord*, xiv. (1886), p. 31.

[2] For an account of the Lamprophyres of the classical district of the Plauenscher-Grund, see B. Doss, *Tschermak's Mineral Mittheil.* xi. (1889).

[3] *Zeitsch. Deutsch. Geol. Ges.* xxv. p. 320.

[4] On diorite, its structure and geological relations, consult the memoir on Belgian plutonic rocks by De la Vallée Poussin and A. Renard, *Mém. Acad. Royale Belg.* 1876; Behrens, *Neues Jahrb. Min.* 1871, p. 460; Zirkel, 'Microscopical Petrog.' p. 83. J. A. Phillips, *Q. J. Geol. Soc.* xxxii. p. 155, and xxxiv. p. 471—two valuable papers in which the constitution of some of the "greenstones" of the older geologists is clearly worked out. Many of these ancient rocks are there shown to be forms of doleritic lava, and the change of their original augite into hornblende is traced.

Trachyte[1]—a term originally applied to modern volcanic rocks possessing a characteristic roughness (τραχύς) under the finger, is now restricted to a compact, usually pale, porphyritic, frequently cellular, rock, consisting essentially of sanidine, with more or less triclinic felspar, augite, hornblende, and biotite, sometimes with apatite, and tridymite. It is distinguished from rhyolite, or quartz-trachyte, by the absence of free quartz, and by the smaller proportion of vitreous or microlitic (micro-felsitic) ground-mass. The sanidine crystals present abundant steam-pores and glass-inclusions, as well as hornblende-microlites and magnetite. In some varieties, the ground-mass appears to be entirely composed of microlites; in others, minor degrees of devitrification can be traced, until the ground-mass passes into a glass (trachyte-glass, obsidian). The trachytes of Hungary have been grouped as *Augite-trachyte*, *Amphibole-trachyte*, and *Biotite-trachyte*. Average composition of Trachyte:—silica, 60·0–64·0; alumina, 17·0; protoxide and peroxide of iron, 6·0–8·0; magnesia, 1·0; lime, 3·5: soda, 4·0; potash, 2·0–2·5. Average specific gravity, 2·65.

Trachyte is an abundantly diffused lava of Tertiary and Post-tertiary date. It occurs in most of the volcanic districts of Europe (Siebengebirge, Nassau, Transylvania, Bay of Naples, Euganean Hills); in the Western Territories of the United States[2]; in New Zealand. It also occurs among the Carboniferous lavas of Scotland.

Domite (so named from the Puy-de-Dôme) is a porous loosely aggregated trachyte, having a microlitic ground-mass, through which are dispersed tridymite, sanidine, much plagioclase, hornblende, magnetite, biotite, and specular iron. Soda-trachyte (Pantellerite) is a variety rich in oligoclase, found in Pantelleria.

Phonolite (Nepheline-trachyte, Clinkstone)[3]—a term suggested by the metallic ringing sound emitted by the fresh compact varieties when struck, is applied to a compact, grey or brown, quartzless mixture of sanidine and nepheline, with nosean, hauyne, leucite, pyroxene, hornblende, or mica. The rock is rather subject to decomposition, hence its fissures and cavities are frequently filled with zeolites. An average specimen gave on analysis—silica, 57·7; alumina, 20·6; potash, 6·0; soda, 7·0; lime, 1·5; magnesia, 0·5; oxides of iron and manganese, 3·5; loss by ignition, 3·2 per cent. The specific gravity may be taken as about 2·58. Phonolite is sometimes found splitting into thin slabs which can be used for roofing purposes. Occasionally it assumes a porphyritic texture from the presence of large crystals of sanidine or of hornblende. When the rock is partly decomposed and takes a somewhat porous texture, it resembles normal trachyte.

It is a thoroughly volcanic rock, and generally of Tertiary date. It occurs sometimes filling the pipes of volcanic orifices, sometimes as sheets which have been poured out in the form of lava-streams, and sometimes in dykes and veins, as in Bohemia and Auvergne. Some of the great bosses or eruptive vents connected with the trachyte lavas of the Garleton Hills, Haddingtonshire, have recently been determined by Dr. Hatch to be true phonolites.

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[1] On trachyte, see Zirkel, 'Micro. Petrog.' p. 143. King in vol. i. of 'Explor. 40th Parallel,' p. 578. On the relative age and classification of Hungarian trachytes, Szabó, *Zeitsch. Deutsch. Geol. Ges.* xxix. p. 635, and 'Compte rend. Congrès internationale de Géologie' (1878), Paris, 1880. For the Scottish Carboniferous trachytes see Presidential Address to the Geological Society 1892, and F. H. Hatch, *Trans. Roy. Soc. Edin.* 1892.

[2] It would appear that much of what has been regarded as trachyte in Western America is andesite, consisting essentially of plagioclase, and not of sanidine. The normal trachytes are now described as hornblende-mica-andesites, and the augite-trachytes are hypersthene-augite-andesites, most of the rest being dacites, and some of them rhyolites. Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 456.

[3] Boricky, 'Petrograph. Stud. Phonolitgestein. Böhmens.'—*Archiv Landesdurchforschung Böhmen*, 1874. G. F. Föhr, "Die Phonolite des Hegau's," *Verh. Phys. Med. Ges. Würzburg*, xviii. (1883). F. H. Hatch, *Trans. Roy. Soc. Edin.* 1892.

With the phonolites may be classed Leucite-trachyte, or Leucite-phonolite, where the felspathoid is leucite instead of nepheline, and Nosean-trachyte (Nosean-phonolite), or Hauyne-trachyte (Hauyne-phonolite), with nosean or hauyne taking the place of the felspar of ordinary phonolite.

Andesite—a name originally given by Von Buch to some lavas found in the Andes, is now applied to a large series of rocks distinguished from the trachytes in that their felspar is plagioclase, and passing by the addition of olivine into dolerite and basalt. In fresh examples they are dark grey, or even black rocks with a compact ground-mass, through which striated felspar prisms may generally be observed. They often assume cellular and porphyritic structures. At the one end of the series stand rocks containing free silica (Dacite), while at the other are basalt-like masses of much more basic composition (Augite-andesite). Under the microscope the ground-mass presents more or less of a pale brownish glass with abundant felspar microlites.

Dacite (Quartz-andesite)—composed mainly of plagioclase, quartz, and mica, with a varying amount of sanidine as an accessory constituent, and, by addition of hornblende and pyroxene, graduating into hornblende-andesite. The ground-mass has a felsitic, sometimes spherulitic, glassy, or finely granular base. Composition: silica, 69·36; alumina, 16·23; iron oxides, 2·41; lime, 3·17; magnesia, 1·34; alkalies, 7·08; water, 0·45. Mean specific gravity, 2·60. This rock is extensively developed in the Great Basin and other tracts of western North America among Tertiary and recent volcanic outbursts.

Hornblende-andesite[1] consists of a triclinic felspar (usually oligoclase), with hornblende, augite, or mica. The ground-mass resembles that of trachyte, presenting sometimes remains of a pale glass. The porphyritic minerals frequently show evidence of having been much corroded before consolidation. Composition: silica, 61·12; alumina, 11·61; oxides of iron, 11·64; lime, 4·33; magnesia, 0·61; potash, 3·52; soda, 3·85; ignition, 4·35. Hornblende-andesite is a volcanic rock of Tertiary and post-Tertiary date found in Hungary, Transylvania, Siebengebirge, and in some of the Western Territories of the United States. According to researches by Messrs. Hague and Iddings, gradations from this rock into basalt and hypersthene-andesite can be traced in California, Oregon, and Washington. These rocks, therefore, cannot be said to have sharply defined and distinct forms.[2] Under the name of Hornblende-mica-andesite American petrographers have described a frequent variety of rock throughout the Great Basin, characterised by the vitreous appearance of its felspar, its rough porous trachyte-like ground-mass, and the presence of mica as an essential constituent. This term will include a large proportion of the rocks hitherto classed as trachytes, but in which the felspar proves to be plagioclase and not sanidine.[3]

Pyroxene-andesite—consisting of labradorite or oligoclase, with augite (less frequently a rhombic pyroxene) and abundant magnetite, sometimes with hornblende or mica, forming a dark heavy basalt-like compound, with a compact sometimes more or less distinctly vitreous ground-mass. Composition: silica, 57·15; alumina, 16·10; protoxide of iron, 13·0; lime, 5·75: magnesia, 2·21; potash, 1·81; soda, 3·88. Mean specific gravity, 2·75–2·85.

It was formerly supposed that the pyroxene of the andesites was always augite. But rhombic forms of the mineral have now been frequently detected. Under the name of

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[1] See Zirkel, 'Microscop. Petrog.' p. 122. King, in vol. i. of 'Explor. 40th Parallel,' p. 562. Hague and Iddings, *Amer. Journ. Sci.* xxvi. (1883), p. 230.

[2] *Amer. Journ. Sci.* Sept. 1883, p. 233.

[3] Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 460.

Hypersthene-andesite, certain Tertiary or recent rocks, stretching over vast areas in Western America, have been described as associated with other andesites and basalts. They are black to grey, or reddish-grey, in colour, and vary in texture from dense, thoroughly crystalline forms, to others approaching white glassy pumice, the base under the microscope ranging from a brown glass to a holocrystalline structure. The magnesian silicate is pyroxene, chiefly in the orthorhombic form as hypersthene, but partly also augite. An analysis of the pumiceous form of the rock gave 62 per cent of silica, while the percentage of the same constituent in the glass of the base was found to rise to 69·94.[1]

Pyroxene-andesite occurs in dykes, lava-streams, plateaux, sheets, and neck-like bosses in regions of extinct and active volcanoes, as in the Inner Hebrides, Antrim, Transylvania, Hungary, Santorin, Iceland, Teneriffe, the Western Territories of North America, the Andes, New Zealand, &c. Many of the rocks of these regions now classed under this name have long been known and described as dolerites and basalts. Indeed, there is the closest relation between them and the true olivine-bearing dolerites and basalts. The latter occur among the Tertiary volcanic plateaux of Britain, interstratified with rocks which, not containing olivine, have been placed among the andesites. Neither in their mode of occurrence nor to the eye in hand specimens is there any good distinction to be drawn between them. Under the name of Tholeite some interesting augite-andesites have been described, in which the felspar prisms form a network filled in with granular augite and interstitial matter (intersertal structure). In other varieties of andesite the felspar-mesh has been filled with large crystalline patches of augite, which thus encloses the felspar (ophitic structure).

Tephrite (Nepheline-andesite, Leucite-andesite, Nosean- or Hauyne-andesite)—a group of andesites, in which the felspar is partly replaced by one of the felspathoids, nepheline, leucite, nosean, or hauyne.

Porphyrite—a name for old forms of andesite which have generally undergone considerable alteration, and consequently appear as dull, sometimes earthy, generally reddish or brownish rocks. When fresh they are dark grey or black. They are commonly porphyritic, and show abundant scattered crystals of plagioclase, less commonly of mica. Their texture varies from coarse crystalline to exceedingly close-grained, passing occasionally into vitreous varieties (Yetholm, Cheviot Hills). Rocks of this type have been abundantly poured forth as lavas during Palæozoic time, and they occur as interstratified lava-beds, eruptive sheets, dykes, veins, and irregular bosses. In Scotland they form masses, several thousand feet thick, erupted in the time of the Lower Old Red Sandstone, and others of wide extent and several hundred feet in depth belonging to the Lower Carboniferous period. In Germany porphyrites appear also at numerous points among formations of later Palæozoic age.

Propylite—a name given by Richthofen to certain Tertiary volcanic rocks of Hungary, Transylvania, and the Western Territories of the United States, consisting of a triclinic felspar and hornblende in a fine-grained non-vitreous ground-mass, and closely related to the Hornblende-andesites. Their distinguishing feature is the great alteration which they have undergone, whereby their ferro-magnesian constituents have been converted into chlorite, and their felspars into epidote. Some quartziferous propylites have been described by Zirkel from Nevada, wherein the quartz abounds in liquid inclusions containing briskly-moving bubbles, and sometimes double enclosures with an interior of liquid carbon-dioxide.[2] A specimen from Storm Canon, Fish Creek Mountains, contained silica, 60·58; alumina, 17·52; ferric oxide, 2·77; ferrous oxide, 2·53; manganese, a trace; lime, 3·78; magnesia, 2·76; soda, 3·30; potash, 4·46; carbonic acid, a trace. Loss by ignition, 2·25; specific gravity, 2·6–2·7. The geologists of the Geological Survey of the United States believe that the rocks included under the term "propylite" in the western parts of America represent various stages of the decomposition of granular diorite, porphyritic diorite, diabase, quartz-porphyry, hornblende-andesite, and augite-andesite.[1] The name has been more recently applied by Rosenbusch to rocks which have undergone alteration by solfataric action.

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[1] Whitman Cross, *Bull. U. S. Geol. Survey*, 1883, No. 1. Hague and Iddings, *Amer. Journ. Sci.* xxvi. (1883), p. 226; xxvii. (1884), p. 457.

[2] Zirkel's 'Microscopical Petrography,' p. 110. King, "Exploration of 40th Parallel," vol. i. p. 545. C. E. Dutton's "High Plateaux of Utah" (*U.S. Geographical and Geological Survey of the Rocky Mountains*), chaps. iii. and iv. Hague and Iddings, *Amer. Journ. Sci.* 1883.

iii. Basic Series.

This third series of eruptive rocks is distinguished by its low silica percentage, and the relative abundance of its basic constituents. A similar range of structure can be traced in it as in the other two series. At the one extreme come rocks with a holocrystalline structure like the gabbros. These pass into others of a hemi-crystalline character, where, amid abundant crystals, crystallites, and microlites, there are still traces of the original glass. At the other end lie true basic volcanic glasses, which externally might be mistaken for the pitchstones and obsidians of the acid rocks.

Gabbro[2] (Euphotide)—a group of coarsely crystalline rocks composed of plagioclase (labradorite) or anorthite, magnetite or titaniferous iron, and some ferro-magnesian mineral, which in the normal gabbros is augite or diallage, but may be a rhombic pyroxene, hornblende, olivine, or mica. These minerals occur in allotriomorphic forms, as in granite; but they sometimes assume ophitic relations which lead into the rock termed dolerite. The felspar has often lost its vitreous lustre and passed into the dull opaque condition known as saussurite. The augite is usually in the form of diallage, distinguished by its schiller-spar lustre.

Gabbro occurs as an eruptive rock among the older formations, likewise in large bosses and dykes in volcanic cores of Tertiary age (Mull, Skye). Average composition: silica, 49; alumina, 15; lime, 9·5; magnesia, 9·7; oxides of iron and manganese, 11·5; potash, 0·3; soda, 2·5. Loss by ignition, 2·5; specific gravity, 2·85–3·10.

The following varieties may be noticed: Olivine-gabbro—a granitoid or ophitic compound of plagioclase, augite, olivine, and magnetic or titaniferous iron; good examples are found among the deep-seated parts of some of the Tertiary volcanic vents of the Inner Hebrides. Hypersthene-gabbro or Norite (Hypersthenite, Hyperite, Schillerfels)—with a rhombic pyroxene in addition to or in place of the augite. Troctolite (Forellenstein)—a mixture of white anorthite with dark-green olivine, receives its name from the supposed resemblance of its speckled appearance to that of the side of a trout. Pyroxene-granulite (granular diorite, trap-granulite)—consisting of plagioclase, pyroxene (monoclinic and rhombic), hornblende, and garnet, distinguished by the granular condition of these minerals, and found among gneisses and other schistose rocks; this is probably an altered condition of some original pyroxenic eruptive rock.

Dolerite—an important group of basic rocks, which connect the gabbros with the basalts and include many of the rocks once termed "Greenstones." They are composed of labradorite (or anorthite), with some ferro-magnesian mineral (augite, enstatite, olivine, or mica) and magnetic or titaniferous iron. As a rule, they are holocrystalline, the constituent felspar and pyroxene or olivine being characteristically grouped in ophitic structure, but a little residual glass may occasionally be detected. They occur in bosses, intrusive sheets, and dykes, especially as the subterranean accompaniments of the volcanic action which has thrown out augite-andesites and basalts to the surface.

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[1] G. F. Becker on the Comstock Lode. *Reports of U.S. Geological Survey* 1880–81, and his full memoir in vol. iii. of the *Monographs of U.S. Geol. Survey* (1882). Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 454.

[2] On Gabbro see Lossen, *Z. Deutsch. Geol. Ges.* xix. p. 651. Lang, *op. cit.* xxxi. p. 484. Zirkel on Gabbros of Scotland, *op. cit.* xxiii. 1871. Judd, *Quart. Journ. Geol. Soc.* xlii. (1886), p. 49. G. H. Williams, *Bull. U.S. Geol. Surv.* No. 28 (1886). F. D. Chester, *op. cit.* No. 59 (1890). M. E. Wadsworth, *Geol. Surv. Minnesota*, Bull. 2, 1887.

Normal or ordinary dolerite consists of plagioclase and augite, with magnetite or titanic iron and frequently olivine. Average composition: silica, 45–55; alumina, 12–16; lime, 7–13; magnesia, 3–9; oxides of iron and manganese, 9–18; potash, 0·1; soda, 2–5. Loss by ignition (water, &c.), 0·5–3; specific gravity, 2·75–2·96.

Different names have been proposed for the chief varieties. The most important of these are Olivine-dolerite—a dark, heavy, close-grained finely-crystalline rock, with scattered olivine, apt to weather with a brown crust. Olivine-free dolerite—a similar rock but containing no olivine. Enstatite-dolerite contains enstatite in addition to the other ingredients. Nepheline-dolerite, has the felspar largely or entirely replaced by nepheline (see Nephelinite, p. 172).

As varieties of dolerite depending for their peculiarities mainly upon their antiquity and the consequent alteration they have undergone, we may include the rocks comprehended under the term Diabase.[1] This name was given to certain dark green or black eruptive rocks found in older geological formations, and consisting essentially of triclinic felspar, augite, magnetite or titaniferous iron, apatite, sometimes olivine, usually with more or less of diffused greenish chloritic substances (viridite) which have resulted from the alteration of the augite or olivine. The average composition of typical diabase may be taken to be: silica, 48–50; alumina, 16·0; protoxide of iron, 12–15; lime, 5–11; magnesia, 4–6; potash, 0·8–1·5; soda, 3–4·5; water, 1·5–2. Specific gravity about 2·9. There is generally carbonic acid present, united with some of the lime as a decomposition product. As in ordinary dolerite, gradations may be traced from coarsely crystalline diabase[2] into exceedingly fine-grained and compact varieties (Diabase-aphanite), which sometimes assume a fissile character (Diabase-schiefer) where they have been subjected to crushing or cleavage. Some kinds present a porphyritic structure, and show dispersed crystals of the component minerals (Diabase-porphyry, Labrador-porphyry, Augite-porphyry); or, as in some varieties of diorite, a concretionary arrangement is produced by the appearance of abundant pea-like bodies of a compact felsitic material, imbedded in a compact or finely crystalline ground-mass (Variolite). When the green compact ground-mass contains small kernels of carbonate of lime, sometimes in great numbers, it is called Calcareous aphanite or Calcaphanite. Sometimes the rock is abundantly amygdaloidal. Though, as a rule, free silica does not occur in it, some varieties found to contain this mineral, possibly a secondary product, have been distinguished as Quartz-diabase. The presence of olivine has suggested the name Olivine-diabase as distinguished from the normal kinds in which this mineral is absent. A variety containing hornblende is termed Proterobase. Ophite, a variety occurring in the Pyrenees, contains diallage and epidote (see p. 120).

Diabase occurs both in contemporaneous beds and in intrusive dykes and sheets.

Basalt[3]—a black, extremely compact, apparently homogeneous rock, which breaks with a splintery or conchoidal fracture, and in which the component minerals can only be observed with the microscope, unless where they are scattered porphyritically through the mass (Fig. 32). The minerals consist of plagioclase (labradorite or anorthite), pyroxene (usually augite, but occasionally a rhombic form), olivine, magnetite or titaniferous iron. Many years ago, Andrews detected native iron in the basalt of Antrim, and more recently Nordenskiöld found this substance abundantly diffused in the basalt of Disco Island, occurring even in large blocks like meteorites (*ante*, p. 68). The ground-mass of basalt presents under the microscope traces of glass in which are imbedded minute granules, hairs, needles, and microlites of felspar and augite. The proportion of this base varies within wide limits, insomuch that while in some parts of a basalt it so preponderates that the individual crystals are scattered widely through it, or are drawn out into beautiful streaks and eddies of fluxion structure, in others it almost disappears, and the rock then appears as a nearly crystalline mass, which thus graduates into dolerite and basic andesite. The component minerals frequently appear porphyritically dispersed, especially the olivine, the pale yellow grains of which are characteristic.

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[1] The student will find in the *Zeitschrift. Deutsch. Geol. Ges.* 1874, p. 1, an important memoir by Dathe on the composition and structure of diabase. See also Zirkel's 'Microscop. Petrog.' p. 97.

[2] Michel-Lévy, *Bull. Soc. Géol. France*, 3rd ser. xi. p. 282. Geikie, *Trans. Roy. Soc. Edin.* xxix. p. 487.

[3] On basalt rocks see Zirkel's 'Basaltgesteine,' 1870. Boricky's 'Petrographische Studien en den Basaltgesteinen Böhmens,' in *Archiv für Naturwiss. Landesdurchforschung von Böhmen*, ii. 1873. Allport, *Q. J. Geol. Soc.* xxx. p. 529. Geikie, *Trans. Roy. Soc. Edin.* xxix. Möhl, *Nov. Act. Acad. Leop. Carol.* xxxvi. (1873), p. 74; *Neues Jahrb.* 1873, pp. 449, 824. F. Eichstadt on Basalts of Scania, *Sveriges Geol. Undersök*, ser. c. No. 51, 1882. E. Svedmark, *op. cit.* No. 60, 1883.

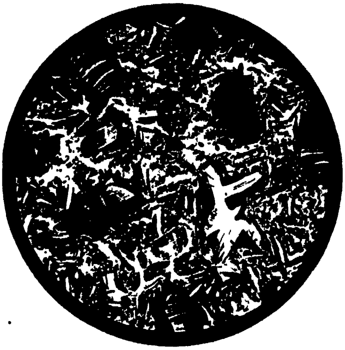

Fig. 32.—Microscopic Structure of Basalt (magnified). The large shaded crystals are Olivine considerably serpentinized: the numerous small white prisms are Plagioclase. A few Augite prisms occur which, to the right of the centre of the drawing, are aggregated into a large compound crystal. The black specks are Magnetite.

Two types of basalt have been recognised in the great basaltic outbursts of Western America: (1) the porphyritic, consisting of a glassy and microlitic or micro-crystalline ground-mass, bearing relatively large crystals of olivine, felspar, and occasionally augite, a structure showing close relations to that of many andesites; (2) the granular (in the sense in which that term is used by Rosenbusch, *ante*, p. 99)—an aggregate of quite uniform grains, composed of well-developed plagioclase and olivine crystals, with ill-defined patches of augite, and frequently with a considerable amount of glass-base. By diminution of olivine and augmentation of silica, and the appearance of hypersthene, gradations can be traced from true olivine-basalts into normal andesites. Basalts with free quartz are not infrequent in Western America.[1]

Basalt occurs in amorphous and columnar sheets, which may alternate with each other or with associated tuffs. It also forms abundant dykes, veins, and intrusive bosses. It frequently assumes a cellular structure, which becomes amygdaloidal by the deposit of calcite, zeolites, or other minerals in the vesicles. A relation may be traced between the development of amygdales and the state of the rock; the more amygdaloidal the rock, the more is it decomposed, showing that the amygdales have probably in large measure been derived by infiltrating water from the basalt itself.

Vitreous Basalt (Basalt-glass, Tachylyte, Hyalomelan).[2]—Basalt passes into a condition which, even to the naked eye, is recognisable as that of a true glass. This more especially takes place along the edges of dykes and intrusive sheets. Where an external skin of the original molten rock has rapidly cooled and consolidated, in contact with the rocks through which the eruption took place, a transition can be traced within the space of less than a quarter of an inch from a crystalline dolerite, anamesite, basalt, or andesite into a black glass, which under the microscope assumes a pale brown or yellowish colour, and is isotropic, but generally contains abundant microlites, sometimes with a globular or spherulitic concretionary structure. In such cases it seems indisputable that this glass represents what was the general condition of the whole molten mass at the time of eruption, and that the present crystalline structure of the rock was developed during cooling and consolidation. The glassy forms of basalt undergo alteration into a yellowish substance called **Palagonite** (p. 138). It is worthy of remark that in the analyses of vitreous basalts, the percentage of silica rises usually above, while their specific gravity falls below, that of ordinary crystalline basalt.

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[1] Hague and Iddings, *Amer. Journ. Sci.* xxvii. (1884), p. 456. Iddings, *op. cit.* xxxvi. (1888), p. 208, *Bull. U. S. Geol. Surv.* Nos. 66 and 79 (J. S. Diller).

[2] See Judd & Cole, *Q. J. Geol. Soc.* xxxix. (1883), p. 444. Cole, *op. cit.* xliv. (1888), p. 300. Cohen, *Neues Jahrb.* 1876, p. 744; 1880 (vol. ii.), p. 23 (Sandwich Islands).

The average composition of basalt is—silica, 45–55 ; alumina, 10–18 ; lime, 7–14 : magnesia, 3–10 ; oxides of iron and maganese, 9–16 ; potash, 0·5–3 ; soda, 2–5. Loss by ignition (water, &c.), 1–5 ; specific gravity, 2·85–3·10.

The basalt-rocks are thoroughly volcanic in origin, appearing in lava-streams, plateaux, sills, necks, dykes, and veins. The columnar structure is so common among the finer-grained varieties that the term "basaltic" has been popularly used to denote it. As already stated, it has been assumed by some writers that basalt did not begin to be erupted until the Tertiary period. But true basalt occurs abundantly in Scotland as a product of Lower Carboniferous volcanoes, and exhibits there a variety of types of minute structure.[1]

Basic Pumice.—Though the acid lavas furnish most of the pumice with which we are familiar, some of the basic kinds also assume a similar structure. Thus at Hawaii, the basic pyroxenic or olivine lavas give rise to a pumiceous froth.

Melaphyre—a name originally proposed by Brongniart and subsequently applied in various senses by different writers to include rocks which range in structure and composition from the more basic andesites to true olivine-basalts. The melaphyres for the most part belong to pre-Tertiary eruptions (though some Tertiary lavas have been described as melaphyre) and have undergone more or less alteration. If the word is to be retained as a definite rock-name it should be restricted to an altered type, as is now generally agreed, and preferentially to the older altered basalts. The melaphyres will then bear somewhat the same relation to the basalts that the diabases do to the dolerites and the porphyrites to the andesites. But it must necessarily happen that difficulty will be experienced in deciding which of the three names would be best applied to some of the eruptive rocks of the older geological formations. The melaphyres, as thus defined, are somewhat dull, dark brown, reddish, or green rocks, often amygdaloidal and showing their porphyritic minerals in an altered condition, the olivines especially being changed into serpentine or replaced by magnetite or even by hæmatite.[2]

Nepheline-basalt (Nepheline-Basanite).—Zirkel proved that certain black heavy rocks, having externally the aspect of ordinary basalt, contain little or no felspar, the part of that mineral being taken in some by nepheline, in others by leucite.[3] They are volcanic masses of late Tertiary age, but occur much more sparingly than the true basalts. They are found in the Odenwald, Thuringer Wald, Erzgebirge, Baden, &c. Mean composition—silica, 45·52 ; alumina, 16·50 ; ferric and ferrous oxides, 11·20 ; lime, 10·62 ; magnesia, 4·35 ; potash, 1·95 ; soda, 5·40 ; water, 2·68. Mean specific gravity, 2·9–3·1. **Nephelinite** is a form of basalt with no felspar or olivine.

Leucite-basalt (Leucite-Basanite) contains little or no felspar, but has leucite in place of it. Externally it resembles ordinary basalt. This rock occurs among the extinct volcanoes of the Eifel and of Central Italy, and forms the lavas of Vesuvius. Leucitite contains no felspar and no olivine.

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[1] See *Trans. Royal. Soc. Edin.* xxix. (1879), p. 437, and Presidential Address, *Quart. Journ. Geol. Soc.* (1892), p. 129, where the types of microscopic structure observed by Dr. Hatch are enumerated.

[2] For some account of the use of the word melaphyre see Brongniart, 'Classification et Caractères minéralogiques des Roches homogènes et hétérogènes,' 1827, p. 106. Naumann, 'Lehrbuch der Geognosie,' i. p. 587. Zirkel, 'Petrographie,' ii. p. 39. Rosenbusch, 'Mikroskop. Physiogr.' ii. p. 484.

[3] 'Basaltgesteine,' 1870.

Melilite-Basalt.—In continuation of Zirkel's research, A. Stelzner has shown that in some basalts the part of felspar and nepheline is played by melilite.[1] In outer appearance the rocks possessing this composition, and to which the name of Melilite-basalt has been given, cannot be distinguished from ordinary basalt. Under the microscope, the ground-mass appears to be mainly composed of transparent sections of melilite, either disposed without order, or ranged in fluxion lines round the large olivine and augite crystals; but it also contains chromite (?), microlitic augite, brown mica, abundant magnetite, with perowskite, apatite, and probably nepheline. (Swabian Alb, Bohemia, Saxon Switzerland, &c.)

Under the awkward name of "ultra-basic," the following group of rocks is included in which the proportion of silica sinks to a still smaller amount than in the basalts.

Limburgite (Magma-basalt)—a fine-grained to vitreous rock composed of augite, olivine, magnetite or titaniferous iron, and apatite. The base is generally glassy and the proportion of silica in the rock is only about 42 per cent. The typical locality is Limburg, near the Kaiserstuhl in Baden.

Peridotite Group.—The rocks here embraced, stand at the extreme end of the basic igneous rocks as the rhyolites and granites stand at the opposite end of the acid series. They contain no felspar, or at least an insignificant proportion of it, and consist of olivine, with augite, hornblende or mica, magnetic or titaniferous iron, chromite and other allied minerals of the spinel type. They contain—silica, 39–45; alumina, 0–6; ferrous oxide, 8–10; lime, 0–2; magnesia, 35–48; and have a mean specific gravity between 3·0 and 3·3. When quite fresh these rocks have a holocrystalline structure, but they are generally more or less altered, and in their extreme condition of alteration form rocks known as serpentines. They occur for the most part as intrusive masses belonging to the deeper-seated portions of volcanic eruptions. The following varieties may be noticed:—

Pikrite[2] (Palaeopikrite, Pikrite-porphyry)—a rock rich in olivine, usually more or less serpentinized, with augite, magnetite, or ilmenite, brown biotite, hornblende, or apatite; occurs as an eruptive rock among Palæozoic formations; is closely related to the diabases into which by the addition of plagioclase it naturally passes. When hornblende predominates over pyroxene the rock has been called hornblende-pikrite.

Lherzolite[3]—so named from L'herz in the Ariège, is a holocrystalline rock composed of olivine, diallage, and a rhombic pyroxene, with a lesser proportion of a spinelloid sometimes brown (chromite, picotite), sometimes green (pleonast), and iron ores.

Dunite, named by F. von Hochstetter from the Dun Mountain, New Zealand, consists of a granitoid mixture of olivine with chromite or other spinelloid. Such a rock passes naturally by alteration into a serpentine.

Serpentine.[4]—Under this name are included rocks which, whatever may have been their original character and composition, now consist mainly or wholly of serpentine. As already stated, olivine readily passes into the condition of serpentine, while the other minerals may remain nearly unaffected, as is admirably seen in some pikrites. Most serpentine-rocks originally consisted principally of olivine (see Fig. 33.) Diorite, gabbro, and other rocks, consisting largely of magnesian silicates, likewise pass into serpentine. If varieties due to different phases of alteration were judged worthy of separate designation, each member of the peridotites might of course have a conceivable or actual representative among the serpentines. But without attempting this minuteness of classification, we may with advantage treat by itself, as deserving special notice, the massive form of the mineral serpentine from whatsoever rock it may have originated.

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[1] *Neues Jahrb.* (Beilageband), 1883, p. 369-439.

[2] So named from πικρός, bitter, in allusion to the large proportion of bitter-earth (Magnesia)—a character shared by all the peridotites. Gümbel, 'Die Palaeolithischen Eruptivgesteine des Fichtelgebirges': Munich, 1874.

[3] On the eruptive nature of Lherzolite, see A. Lacrois, *Compt. rend.* cxv. (1892), pp. 974, and 976.

[4] See Tschermak, *Sitz. Akad. Wien*, lvi. July, 1867; it was this author who first showed the derivation of serpentine from original olivine rocks; Bonney, *Q. J. Geol. Soc.* xxxiii. p. 884, xxxiv. p. 769; *Geol. Mag.* (2) vi. p. 362; (3) i. p. 406; Michel-Lévy, *Bull. Soc. Géol. France*, vi. 3rd ser. p. 156; Sterry Hunt, *Trans. Roy. Soc. Canada*, i. (1883); Dathe, *Neues Jahrb.* 1876, pp. 236, 337, where Garnet-serpentine and Bronzite-serpentine are described from the Saxon granulite region. J. S. Diller, *Bull. U. S. Geol. Surv.* No. 38 (1887); M. E. Wadsworth, 'Lithological Studies,' (1884), p. 118.

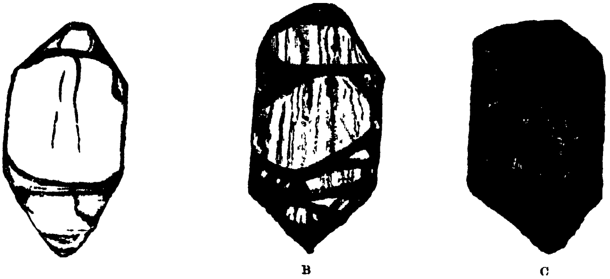

Fig. 33.—Stages in the alteration of Olivine. A, the nearly fresh crystal, B, the alteration half completed; C, the crystal wholly serpentinized.

Massive serpentine is a compact or finely granular, faintly glimmering, or dull rock, easily cut or scratched, having a prevailing dirty-green colour, sometimes variously streaked or flecked with brown, yellow, or red. It frequently contains other minerals besides serpentine. One of its commonest accompaniments is chrysotile or fibrous serpentine, which in veinings of a silky lustre often ramifies through the rock in all directions. Other common enclosures are bronzite, enstatite, magnetite, and chrome-spinels, besides traces of the original olivine, pyroxene, amphibole, mica, or felspar in the rocks which have been altered into serpentine.

Serpentine occurs in two distinct forms; 1st, in beds or bands intercalated among schistose rocks, and associated especially with crystalline limestones; 2ndly, in dykes, veins, or bosses traversing other rocks.

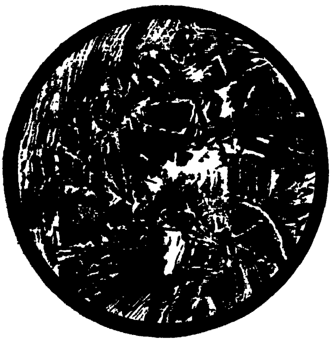

Fig. 34.—Microscopic Structure of Serpentine (20 Diameters).

As to its mode of origin, there can be no doubt that in most cases it was originally an eruptive rock, as is clearly shown by its occurrence in dykes and irregular bosses. The frequent occurrence of recognisable olivine crystals, or of their still remaining contours, in the midst of the serpentine-matrix, affords good grounds for assigning an eruptive origin to many serpentines which have no distinctly eruptive external form (Fig. 34). The rock cannot, of course, have been ejected as the hydrous magnesian silicate serpentine; we must regard it as having been originally an eruptive olivine rock, or a highly hornblendic or micaceous diorite, or olivine-gabbro. But, on the other hand, the intercalation of beds of serpentine among schistose rocks, and particularly the frequent occurrence of serpentine in connection with more or less altered limestones (West of Ireland, Highlands of Scotland) suggests another mode of origin in these cases. Some writers have contended that such serpentines are products of the alteration of dolomite, the magnesia having been taken up by silica, leaving the carbonate of lime behind as beds of limestone. Others have supposed the original rocks, from which the serpentines were derived, to have been a deposit from oceanic water, as has been suggested by Sterry Hunt in the case of those associated with the crystalline schists.[1] Beds of serpentine intercalated with limestone might conceivably have been due to the elimination of magnesian silicates from sea-water by organic agency, like the glauconite now found filling the chambers of *foraminifera*, the cavities of corals, the canals in shells, sea-urchin spines and other organisms on the floor of the present sea.[2] Among the limestone and crystalline schists of Banffshire (p. 183), serpentine occurs in thick lenticular beds which possess a schistose crumpled structure and agree in dip with the surrounding rocks. They may have been deposits of contemporaneous origin with the limestones and schists among which they occur, and in association with which they have undergone the characteristic schistose puckering and crumpling. Sometimes they suggest a source from the alteration of highly basic volcanic tuffs. In other cases they may have been erupted peridotites which have acquired a schistose character from the same process of mechanical deformation that has played so large a part in producing the foliation of the crystalline schists.

III. SCHISTOSE (METAMORPHIC).

In this section is comprised a series of rocks which present a remarkable system of divisional planes that are not original but have been superinduced upon them. At the one end stand rocks which are unmistakably of sedimentary origin, for their original bedding can often be distinctly seen, and they also contain organic remains similar to those found in ordinary unaltered sedimentary strata. At the other end come coarsely crystalline masses, which in many respects resemble granite, and the original character of which is not obvious. An apparently unbroken gradation can be traced between these extremes, and the whole series has been termed "metamorphic" from the changed form in which its members are believed now to appear. In the earlier stages the change has taken the form of cleavage as in ordinary slate. Even in slate, however, as already remarked (p. 134), a beginning may be detected in the development of crystalline particles, and the crystalline re-arrangement may be traced in constantly advancing progression until the whole mass has become crystalline, and forms what is known as a schist.

The Crystalline Schists, properly so called, constitute a well-defined series of rocks. They are mainly composed of silicates. Their structure is crystalline, but is distinguished from that of the Massive or Eruptive rocks by its more or less closely parallel layers or folia, consisting of materials which have assumed a crystalline character along these layers. The folia may be composed of only one mineral, but usually consist of two or more, which occur either in distinct, often alternate laminæ, or intermingled in the same layer. This structure resembles that of the stratified rocks, but it is differentiated (1) by a prevalent, striking want of continuity in the folia, which, as a rule, are conspicuously lenticular, thickening out and then dying away, and reappearing after an interval on the same or a different plane (Fig. 35); (2) by a peculiar and very characteristic welding of the folia into each other, the crystalline particles of one layer being so intermingled with those of the layers above and below it that the whole coheres as a tough, not easily fissile mass ; (3) by a frequent remarkable and eminently distinctive puckering or crumpling (with frequent minute faulting) of the folia, which becomes sometimes so fine as to be discernible only under the microscope[1] (Fig. 37), but is often present conspicuously in hand-specimens (Fig. 36), and can be traced in increasing dimensions, till it connects itself with gigantic curvatures of the strata, which embrace whole mountains. These characters are sufficient to indicate a great difference between schistose rocks and ordinary stratified formations, in which the strata lie in continuous flat, parallel, and more or less easily separable layers.

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[1] 'Chemical Essays,' p. 123.

[2] According to Berthier, one of the glauconitic deposits in a Tertiary limestone is a true serpentine. See Sterry Hunt, 'Chem. Essays,' p. 303.

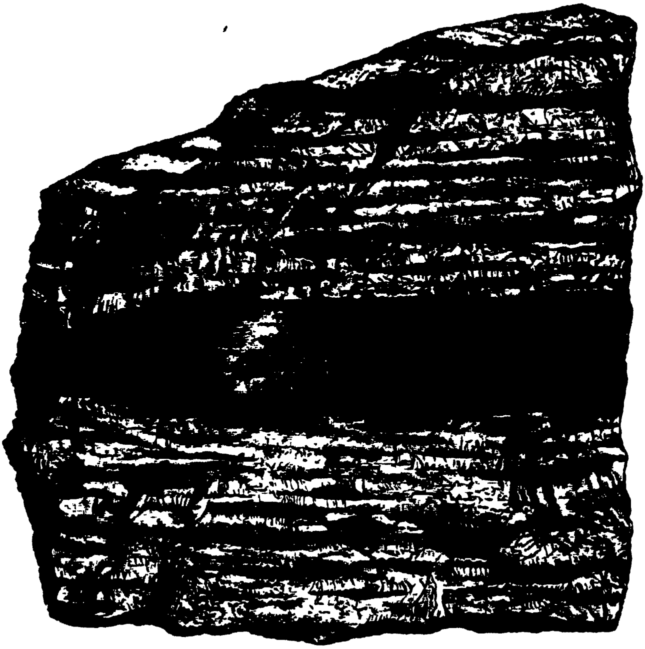

Fig. 35.—Profile of a piece of Gneiss, showing the lenticular character of its folia, natural size. (B. N. Peach.)

In some instances, the folia can be seen to coincide with original bedding, as where a band of quartzite or of conglomerate is intercalated between sheets of phyllite or mica-schist. In such cases, there cannot be any doubt that the rock, though now more or less re-constructed and crystalline, was originally mere accumulated mechanical sediment. Many clay-slates, phyllites, and mica-schists are obviously only altered marine clays, and some of them still retain their recognisable fossils. From such rocks, gradations can be followed into chiastolite-schist, mica-schist, and fine gneiss. Quartzites and quartz-schists often still retain the false-bedding of the original sandy sediment of which they are composed. The pebbly and conglomeratic bands associated with some schists afford convincing proof of their original clastic nature. Thus, at the one end of the schistose series we find rocks in which an original sedimentary character remains unmistakable. At the other end, after many intermediate stages, we encounter thoroughly amorphous crystalline masses, that bear the closest resemblance to eruptive rocks into which they insensibly pass. In such instances, there can be little doubt that the amorphous structure is the original one, which has become schistose by subsequent deformation (Book IV. Part VIII.) The banded arrangement of many coarse gneisses, however, may be an original segregation-structure, like that observable in sills and bosses of eruptive rocks (p. 615).

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[1] On the microscopic structure of the crystalline schists see Zirkel, 'Microscopical Petrography' (vol. vi. of King's Exploration of 40th Parallel), 1876, p. 14. Allport, *Q. J. Geol. Soc.* xxxii. p. 407. Sorby, *op. cit.* xxxvi. p. 81, Lehmann's 'Untersuchungen über d. Entstehung. Altkryst. Schiefer,' Bonn, 1884; and other memoirs cited in subsequent

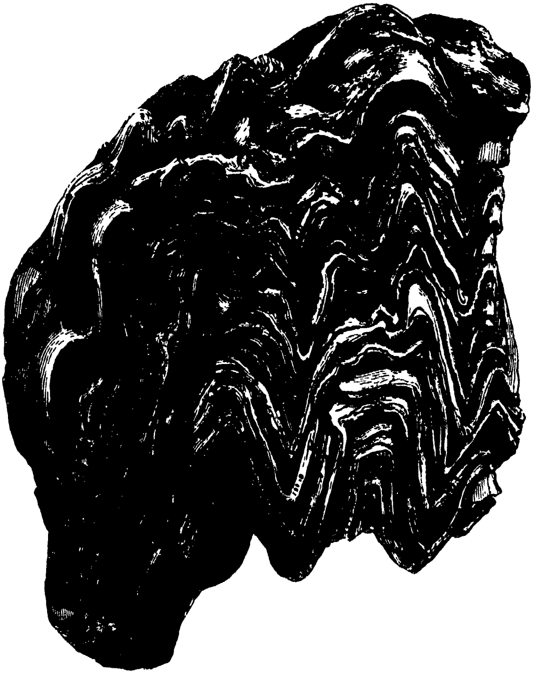

Fig. 36.—View of a hand-specimen of contorted mica-schist, two-thirds natural size. (B. N. Peach.)

In the more thoroughly re-constructed and re-crystallized schists all trace of the original structures has been lost. The foliation is not coincident with bedding, nor with any structure of eruptive rocks, but has been determined by planes of cleavage or of shearing, or by the alignment assumed by minerals crystallizing under the influence of intense pressure. Along these surfaces the constituents have rearranged themselves, and new chemical and mineralogical combinations have been effected during the progress of the "metamorphism."

A rock possessing a crystalline arrangement into separate folia is in English termed a Schist.[1] This word, though employed as a general designation to describe the structure of all truly foliated rocks, is also made use of as a suffix to the names of the minerals of which some of the foliated rocks largely consist. Thus we have "mica-schist," "chlorite-schist," "hornblende-schist." If the mass loses its fissile tendency, owing to the felting together of the component mineral into a tough coherent whole, the word rock is usually substituted for schist, as in "hornblende-rock," "actinolite-rock," and so on. The student must bear in mind that while the possession of a foliated structure is the distinctive character of the crystalline schists, it is not always present in every individual bed or mass associated with these rocks. Yet the non-schistose portions are so obviously integral parts of the schistose series that they cannot, without great violation of natural affinities, be separated from them. Hence in the following enumeration they are included as common accompaniments of the schists. Quartzite also may be placed in this subdivision, though in its typical condition it shows no schistose structure.

The origin of the crystalline schists has been the subject of long discussion among geologists. Werner held that, like other rocks of high antiquity, they were chemical precipitates from a universal ocean. Hutton and his followers maintained that they were mechanical aqueous sediments altered by subterranean heat. These two doctrines in various modifications are still maintained by opposite schools. In recent years much light has been thrown upon the origin of the schistose structure, which has been shown to be in many cases due to the mechanical crushing and chemical re-adjustment and re-crystallization of the materials of both sedimentary and igneous rocks. This subject is discussed in a later part of this volume. (See Book IV. Part VIII.)

It is obvious that a wide series of rocks embracing variously altered forms of both sedimentary and igneous materials hardly admits of any simple system of classification. Regarding them from the point of view of the nature of the metamorphism they have undergone, geologists have sometimes grouped these rocks as resulting either from contact metamorphism, that is, from the effects of the protrusion of igneous matter from within the earth's interior, or from regional metamorphism where the changes have been brought about by some widespread terrestrial disturbance (Book IV. Part VIII.) But this arrangement, though of value in discussing questions of metamorphism, has the disadvantage of introducing theoretical considerations, and of placing in different groups rocks which undoubtedly present the same general petrographical characters. Avoiding all disputed questions as to modes of origin, I shall group the schists according to their mineral characters, beginning with those which are obviously only a further stage of the alteration of clay-slates, and ending with the gneisses, which bear a close affinity to granites.

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[1] In French this term has no such definite signification, being applied both to schists and to shales. In German also the corresponding word "schiefer" designates schists, but is also employed for non-crystalline shaly rocks ; thonschiefer = clay-slate : schieferthon = shale.

1. ARGILLITES, ARGILLACEOUS SCHISTS, PHYLLITES.—The rocks included in this group may often be traced into the clay-slates described on p. 134. They mark a further stage of metamorphism, wherein besides mechanical deformation there has been a more or less decided re-crystallization of the materials, which is demonstrated by the abundant secondary mica and by the appearance of such minerals as chiastolite, andalusite, staurolite, garnet, &c. When a clay-slate becomes lustrous by the development of mica, it is known as Phyllite—a term which may be regarded as embracing the intermediate group of rocks between normal clay-slates and true mica-schists.

Chiastolite-slate (schiste maclé), a clay-slate in which crystals of chiastolite have been developed, even sometimes side by side with still distinctly preserved graptolites or other organic remains [1] (Skiddaw, Aberdeenshire, Brittany, the Pyrenees, Saxony, Norway, Massachusetts, &c.) Staurolite-slate, a micaceous clay-slate with crystals of staurolite (Banffshire, Pyrenees). Ottrelite-slate, a clay-slate marked by minute, six-sided, greyish or blackish green lamellæ of ottrelite (Ardennes, where it is said to contain remains of trilobites, Bavaria, New England). Dipyre-slate is full of small crystals of dipyre. Sericite-phyllite is a name proposed by Lossen for those compact, greenish, reddish, or violet sericite-schists in which the naked eye can no longer distinguish the component minerals. Mica-phyllite (*phyllade gris feuilleté* of Dumont), a silky, usually very fissile slate, with minute scales of mica. German petrographers have distinguished by name some other varieties found in metamorphic areas and characterised by different kinds of concretions, but to which no special designations have been given in English. Knotenschiefer (Knotted schist) contains little knots or concretions of a dark-green or brown, fine-granular, faintly glimmering substance, of a talcose or micaceous nature, imbedded in a finely-laminated matrix of a talc-like or mica-like mineral.[2] These aggregations appear to be in many cases incipient stages in the formation of definite crystals of such minerals as andalusite. In Fruchtschiefer the concretions are like grains of corn; in Garbenschiefer, like caraway seeds; in Fleckschiefer, like flecks or spots. Some of these rocks might be included with the mica-schists, into varieties of which they seem to pass. Round some of the eruptive diabase of the Harz, the clay-slates have been altered into various crystalline masses to which names have been attached. Thus Spilosite is a greenish, schistose rock, composed of finely granular or compact felspathic material, with small chlorite concretions or scales. Desmosite is a schistose mass in which similar materials are disposed in more distinct alternations.[3]

2. QUARTZ ROCKS.[4]—**Quartz-schist** (schistose quartzite), an aggregate of granular (or

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[1] A good illustration of this association is figured by Kjerulf in his 'Geologie des Südlichen und Mittleren Norwegen,' Plate xiv. fig. 246. See also Brogger's memoir on Upper Silurian fossils among the crystalline rocks of Bergen. Christiania, 1882. A similar association occurs in the graptolite-shales next the granite of Galloway, Scotland.

[2] A. von Lasaulx, *Neues Jahrb.* 1872, p. 840. K. A. Lossen, *Z. Deutsch. Geol. Ges.* 1867, p. 585 (where a detailed description of the Taunus phyllites will be found), 1872, p. 757.

[3] Other names are *Bandschiefer*, *Contactschiefer*, &c. See K. A. Lossen. *Zeitsch. Deutsch. Geo. Ges.* xix. (1867), p. 509, xxi. p. 291, xxiv. p. 701. Kayser, *op. cit.* xxii. p. 103.

[4] J. Macculloch, *Trans. Geol. Soc.* 1st ser. ii. (1814), p. 450, iv. (1817), p. 264; 2nd ser. i. (1819), p. 53. Lossen, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867), pp. 615-634.

granulitic) quartz with a sufficient development of fine folia of mica to impart a more or less definitely schistose structure to the rock. The disappearance of the mica gives quartzite, and the greater prominence of this mineral affords gradations into mica-schist. Such gradations are quite analogous to those among recent sedimentary materials from pure sand, through muddy sand, and sandy mud, into mud or clay, and between sandstones and shales. The Highlands of Scotland, for instance, embrace large tracts of quartz-schists—rocks which are not properly either mica-schist or ordinary quartzite. They consist of granular (granulitized) quartz, with fine parallel laminæ of mica, and are capable of being split into thick or thin flagstones. Interstratified pebbly varieties occur.

Itacolumite—a schistose quartzite, in which the quartz-granules are separated by fine scales of mica, talc, chlorite, and sericite. Occasionally these pliable scales are so arranged as to give a certain flexibility to the stone (flexible sandstone). This rock occurs in the south-eastern states of North America; also in Brazil, as the matrix in which diamonds are found.

Siliceous schist (Lydian stone, Lydite, Kieselschiefer) has already been described (p. 154) among the stratified rocks; but it also occurs among the crystalline schists, sometimes as the result of the pulverisation of quartzose rocks (mylonite).

Quartzite (Quartz-rock), though not properly a schistose rock, may be most conveniently considered here, as it is so constant an accompaniment of the schists, and, like them, can often be directly traced to the alteration of former sedimentary formations. It is a granular to compact mass of quartz, generally white, sometimes yellow or red with a characteristic lustrous fracture. It occurs in thin and thick beds in association with schists, sometimes in continuous masses several thousand feet thick. In Scotland it forms ranges of mountains, and is there frequently accompanied by beds of limestone, which in Sutherlandshire contain Cambrian fossils.[1]

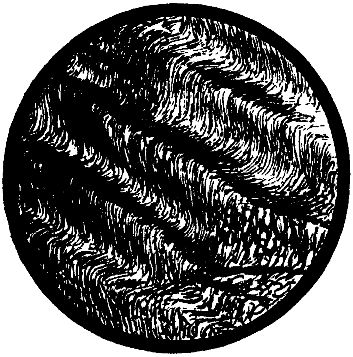

Fig. 37.—Contorted Micaceous-schist, as seen under the microscope with a magnifying power of 50 diameters.

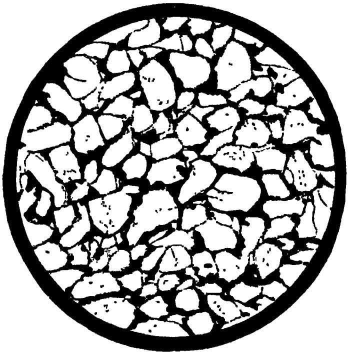

Fig. 38.—Microscopic Structure of Quartzite. (Magnified 20 diameters.)

Even to the naked eye, the finely granular or arenaceous structure of quartzite is distinctly visible. Microscopic examination shows this structure still more clearly, and leaves no doubt that the rock originally consisted of a tolerably pure quartz-sand (Fig. 38). More or less distinct evidence of crushing and deformation of the grains may often be observed, likewise proof of the transfusion of a siliceous cement among the particles. This cement was probably produced by the solvent action of heated water upon the quartz grains, which seem to shade off into each other, or into the intervening silica. It is owing, no doubt, to the purely siliceous character of the grains that the blending of these with the surrounding cement is so intimate as often to give the rock an almost flinty homogeneous texture. That quartzite, as here described, is an original sedimentary rock, and not a chemical deposit, is shown not only by its granular texture, but by the exact resemblance of all its leading features to ordinary sandstone—false-bedding, alternation of coarser and finer layers, worm-burrows, and fucoid-casts. The lustrous fracture that distinguishes this rock from sandstone, is due to the exceedingly firm cohesion of the component grains, which break across rather than separate, and to the consequent production of innumerable minute clear vitreous surfaces of quartz. A sandstone, on the other hand, has its grains so loosely coherent that when the rock is broken, the fracture passes between them, and the new surface obtained presents innumerable dull rounded grains.

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[1] See the chapters on the Pre-Cambrian and Cambrian systems *postea.* On the metamorphic quartzose rocks of Morbihan, France, see Barrois, *Ann. Soc. Géol. Nord*, xi. (1884).

Besides occurring in alternation with schists, quartzite is also met with locally as an altered form of sandstone, which when traversed by igneous dykes, is indurated for a distance of a few inches or feet from the intrusive mass. These local productions of quartzite show the characteristic lustrous fracture, and have not yet been distinguished by the microscope from the quartz-rock of wide metamorphic regions. There is yet another condition under which this rock, or one of analogous structure, may be seen. Highly silicated bands, having a lustrous aspect, fine grain, and great hardness, occur among the unaltered shales and other strata of the Carboniferous system. In such cases the supposition of any general metamorphism being inadmissible, we may infer either that these quartzose bands have been indurated, for example, by the passage through them of thermal silicated water, or that they are an original formation.

Schistose Conglomerate Rocks.—In some regions of schists, not only bands of quartzite occur, representing former sandstones, but also pebbly or conglomeratic bands, in which pebbles of quartz and other materials from less than an inch to more than a foot in diameter are imbedded in a foliated matrix, which may be phyllite, mica-schist, gneiss, quartzite, &c.[1] Examples of this kind are found in the pass of the Tête Noire between Martigny and Chamouni, in the Saxon granulite region, in the Bergen region of Norway, in the north-west of France, in north-west Ireland, in the islands of Islay and Garvelloch, and in Perthshire and other parts of the central Highlands of Scotland. The pebbles are not to be distinguished from the water-worn blocks of ordinary conglomerates; but the original matrix which encloses them has been so altered as to acquire a micaceous foliated structure, and to wrap the pebbles round as with a kind of glaze. These facts, like those already referred to in the structure of quartzite and argillaceous and quartz-schist, are of considerable value in regard to the theory of the origin of some crystalline schists.

3. PYROXENE-ROCKS.—**Augite-schist**—a fine grained schistose aggregate of pale or dark-green augite, with sometimes quartz, plagioclase, magnetite, or chlorite; found rarely among the crystalline schists. Among the schistose rocks of the Taunus, Lossen has described some interesting varieties under the name of Augite-schist (Augitschiefer). They are green, compact, sometimes soft and yielding to the finger-nail, usually distinctly schistose, and interbedded with the gneisses and schists. They are composed of a fine dull diabase-like ground-mass, through which are dispersed crystals of augite, 1 to 2 mm. in length, which in the typical varieties are the only components distinctly recognisable by the naked eye.[2] **Augite-rock**—a granular aggregate of augite (with tourmaline, sphene, scapolite, etc.), found in beds in the Laurentian limestone of Canada. Malacolite-rock is a pale granular to compact, or even fibrous aggregate of malacolite found in beds

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[1] Prof. Wichmann describes some curious examples of serpentine conglomerates. See his paper in "Beiträge zur Geologie Ost-Asiens und Australiens," ii. pp. 35, 111. On the conglomerate-schists of Saxony, see A. Sauer, 'Geol. Specialkarte Sachsen,' Sect "Elterlein," also Lehmann's 'Altkryst. Schiefergesteine,' p. 124. Reusch, 'Silurfossiler og Pressede Konglomerater,' Christiania, 1882. Barrois, *Ann. Soc. Géol. Nord.* xi. 1884.

[2] Lossen, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867), p. 598.

in crystalline limestone (Riesengebirge). **Schistose Gabbro**—a granular to schistose aggregate of plagioclase and diallage, occurs in lenticular bands among the amphibolites and granulites of the crystalline schists. The diallage may occur in conspicuous crystals, and is sometimes associated with abundant olivine, as in ordinary gabbro (p. 154).[1]

These pyroxenic intercalations among the schists, like the hornblendic and olivine bands mentioned below, seem to represent bands of igneous material (lavas or tuffs) either erupted contemporaneously with the deposition of the original material of the schists, or subsequently intruded into it, and thereafter exposed to the metamorphism which produced the foliation of the schists.

4. HORNBLENDE-ROCKS.—**Amphibolites**—a name applied to a group of rocks, composed mainly of hornblende, sometimes schistose, sometimes thick-bedded. Besides the hornblende, numerous other minerals, such as are common among the schists, likewise occur,—orthoclase, plagioclase, quartz, augite and varieties, garnet, zoisite, mica, rutile, &c. Where the rock is schistose, it becomes an **amphibolite-schist** or **hornblende-schist**; or if the hornblende takes the form of actinolite, Actinolite-schist. Glaucophane-schist—a bluish-grey or black rock, in which the hornblende occurs in the form of glaucophane, forms large masses in the Southern Alps, and occurs locally in Anglesey. Where an amphibolite is not schistose, it used to be termed *hornblende-rock.* Nephrite (Jade) is a compact, extremely finely fibrous variety. The presence of other minerals in noticeable quantity may furnish names for other varieties. Thus, where plagioclase (and some orthoclase) occurs, the rock becomes a Felspar-amphibolite, Dioritic amphibolite, or Diorite-schist.[2] Amphibolites occur as bands associated with gneiss and other schistose formations. It was suggested by Jukes that they may possibly represent former beds of hornblendic or augitic lava and tuff, which have been metamorphosed together with the strata among which they were intercalated. This suggestion has received confirmation from the researches of the Geological Survey in the north of Scotland and in Ireland, where what were doubtless originally pyroxenic masses erupted prior to the metamorphism of the region, have had their augite changed by paramorphism into hornblende, and have partially assumed a foliated structure, passing into Epidiorite, Epidiorite-schist, amphibolite-schists, and even serpentine. The connection of some schists with original masses of diorite, gabbro, and diabase has been pointed out by Lehmann and subsequently by many other observers.[3]

5. GARNET-ROCKS.—**Eclogite**, one of the most beautiful members of the crystalline-schist series, is a granular aggregate of grass-green omphacite (pyroxene) and red garnet, through which are frequently dispersed bluish kyanite and white mica. It occurs in bands in the Archæan gneiss and mica-schist. To those varieties where the kyanite becomes predominant, the name of Kyanite-rock has been given. Garnet-rock is a crystalline-granular rock composed mainly of garnet, with hornblende and magnetite; by the diminution of the garnet it passes into an amphibolite. Kinzigite—a crystalline schistose rock, composed of plagioclase, garnet, and black mica, found in the Black Forest (Kinsig) and the Odenwald.

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[1] Rocks of this character occur in the Saxon "Granulitgebirge" and also in Lower Austria. F. Becke, Tschermak's *Min. Mitth.* IV. p. 352. J. Lehmann's 'Untersuchungen über die Entstehung der Altkrystallinischen Schiefergesteine,' Bonn, 1884, p. 190. On the diabase-schists of the Taunus, see L. Milch, *Zeitsch. Deutsch. Geol. Ges.* xli. (1889), p. 394.

[2] See F. Becke, Tschermak's *Min. Mitth.* IV. p. 233. This author likewise distinguishes *diallage-amphibolite, garnet-amphibolite, salite-amphibolite, zoisite-amphibolite.*

[3] 'Untersuchungen über die Entstehung der Altkrystall. Schief.' See also Gümbel, 'Die Paläolitischen Eruptivgesteine des Fichtelgebirges,' Munich, 1874, p. 9; Teall, *Quart. Journ. Geol. Soc.* xli. (1883), p. 133; 'British Petrography,' p. 198. Hatch, *Mem. Geol. Survey, Explanation of Sheets,* 138, 139, *Ireland,* p. 49. Hyland, *Mem. Geol. Survey, Explanations of North-west Donegal, and of South-west Donegal,* Petrographical appendices, also *postea,* Book IV. *pt.* viii. G. H. Williams, *Bull. U.S. Geol. Surv.* No. 62, 1890.

6. EPIDOTE-ROCKS.—**Epidosite** (Pistacite-rock)—an aggregate of bright green epidote with some quartz, occurs with chlorite-schist (Canada), with granite and serpentine (Elba), and with syenite. Epidote-schist, a schistose greenish rock, with silvery lustre on the foliation surfaces, composed of epidote, sericite, magnetite, quartz, calcite, plagioclase, and specular iron.[1]

7. CHLORITE-ROCKS.—**Chlorite-schist**—a scaly schistose aggregate of greenish chlorite, usually with quartz and often with felspar, talc, mica, or magnetite, the last-named mineral frequently appearing in beautifully perfect disseminated octohedra. Occurs with gneiss and other schists in evenly bedded masses.

8. TALC-ROCKS.—**Talc-schist**—a schistose aggregate of scaly talc, often with quartz, felspar, and other minerals ; having an unctuous feel, and white or greenish colour. Occurs somewhat rarely in beds associated with mica-schist and clay-slate, and frequently contains magnetite, chlorite, mica, kyanite, and other minerals, including carbonates. A massive variety, composed of a finely felted aggregate of scales of talc, with chlorite and serpentine, is called Potstone (Topfstein). Many rocks with a soapy or unctuous feel have been classed as talc-schist, which contain no talc, but a variety of mica (sericite-schist, &c.) Talc-schist, though not specially abundant, occurs in considerable mass in the Alps (Mont Blanc, Monte Rosa, Carinthia, etc.), and is found also among the Apennine and Ural mountains.

9. OLIVINE-ROCKS, or PERIDOTITES of the Crystalline Schists.[2] Rocks of which olivine forms a main constituent, occur as subordinate bands or irregular masses associated with gneisses and other schistose rocks. They were probably eruptive masses, contemporaneous with or subsequent to the surrounding gneisses and schists (p. 182). The olivine is commonly associated with some pyroxenic mineral, hornblende, garnet, &c. Some of the rocks mentioned on p. 173 may also be included here. Dunite, for example, which occurs in apparently eruptive form at Dun Mountain, near Nelson, New Zealand, is found in North Carolina in beds with laminated structure intercalated in hornblende-gneiss. Many of these rocks have undergone much crushing and deformation, and pass into foliated forms of Serpentine, which must thus be reckoned as one of the schistose as well as one of the eruptive series. Some remarkable schistose serpentines occur interbedded among phyllites, mica-schists, and limestones in Banffshire.

10. FELSITOID-ROCKS.—These are distinguished by an exceedingly compact felsite-like matrix. They occur in beds or bed-like masses, sometimes in districts of contact metamorphism, sometimes associated with vast masses of schists.

Hälleflinta—an exceedingly compact, hornstone-like, felsitic, grey, yellowish, greenish, reddish, brownish, or black, rock, composed of an intimate mixture of microscopic particles of felspar and quartz, with fine scales of mica and chlorite. It breaks with a splintery or conchoidal fracture, presents under the microscope a finely-crystalline structure, occasionally with nests of quartz, and is only fusible in fine splinters before the blow-pipe. Some of the rocks to which this name has been applied are probably felsitic lavas ; others, though externally presenting a resemblance to felsite, occur in beds intimately associated with foliated rocks (Norway), and may be metamorphic products (perhaps altered fine sediments) due to the same series of changes that gave rise to the crystalline schists among which they lie.[3]

Adinole (Adinole-schist)—a rock externally resembling the last, but distinguished from it by its greater fusibility. It is an intimate mixture of quartz and albite, containing about ten per cent of soda. It is a product of alteration, being found among the altered Carboniferous shales around the eruptive diabases of the Harz, in the altered Devonian rocks of the Taunus, and in the altered Cambrian rocks of South Wales.[1]

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[1] See Wichmann on Rocks of Timor, "Beitrage zur Geologie Ost-Asiens und Australiens," II. part 2, p. 97, Leyden, 1884.

[2] See Tschermak, *Sitzb. Akad. Wissen.*, Vienna, lvi. (1867). F. Becke, Tschermak's *Min. Mitth.* IV. (1882), p. 322. E. Dathe, *Neues Jahrb.* 1876, pp. 255-337.

[3] For analyses see H. Santesson, "Kemiska Bergsartanalyser," 8vo, Stockholm, 1877.

Porphyroid—a name bestowed upon certain rocks composed of a felsite-like groundmass which has assumed a more or less schistose structure from the development of micaceous scales, and which contains porphyritically scattered crystals of felspar and quartz. The felspar is either orthoclase or albite, and may be obtained in tolerably perfect crystals. The quartz occasionally presents doubly terminated pyramids. The micaceous mineral may be paragonite or sericite. Porphyroid occurs in circumstances which suggest considerable mechanical deformation, as among the schistose rocks of Saxony,[2] in the Palæozoic area of the Ardennes,[3] as well as in Westphalia and other parts of Europe.[4] Some porphyroids are probably sheared forms of quartz-porphyry, felsite, or some similar rock ; others may be more of the nature of tuffs.

11. QUARTZ- AND TOURMALINE-ROCKS.—**Tourmaline-schist** (Schorl-schist, schorl-rock), a blackish, finely granular, quartzose rock with abundant granules and needles of black tourmaline (schorl), which occurs as one of the products of contact-metamorphism in the neighbourhood of some granites (Cornwall).

12. QUARTZ- AND MICA-ROCKS.—**Mica-schist** (Mica-slate, Glimmerschiefer), a schistose aggregate of quartz and mica, the relative proportions of the two minerals varying widely even in the same mass of rock. Each is arranged in lenticular wavy laminæ. The quartz shows great inconstancy in the number and thickness of its folia. It often presents a granular character, like that of quartz-rock, or passing into granulite. The mica lies in thin plates, sometimes so dovetailed into each other as to form long continuous irregular crumpled folia, separating the quartz layers, and often in the form of thin spangles and membranes running in the quartz. (Figs 36 and 37.) As the rock splits open along its micaceous folia, the quartz is not readily seen save in a cross fracture.

The mica in typical mica-schist is generally a white variety ; but it is sometimes replaced by a dark species. In many lustrous, unctuous schists which are now found to have a wide extent, the silvery foliated mineral is ascertained to be a mica (margarodite, damourite, etc.), and not talc, as was once supposed. These were named by Dana hydro-mica-schists. Among the accessory minerals, garnet (specially characteristic), schorl, felspar, hornblende, kyanite, staurolite, chlorite, and talc may be mentioned. Mica-schist readily passes into other members of the schistose family. By addition of felspar, it merges into gneiss. By loss of quartz and increase of chlorite, it passes into chlorite-schist, and by loss of mica, into quartz-schist and quartzite. By failure of quartz and diminution of mica, with an increasing admixture of calcite, it may shade into calc-mica-schist (see below), and even into marble. Mica-schist varies in colour mainly according to the hue of its mica.

Mr. Sorby has stated that thin slices of some mica-schists, when examined under the microscope, show traces of original grains of quartz-sand and other sedimentary particles of which the rock at first consisted. He has also found indications of what he supposes to have been current-bedding or ripple-drift, like that seen in many fine sedimentary deposits, and he concludes that mica-schist is a crystalline metamorphosed sedimentary rock.[5] In many, if not in most cases, however, the foliation does not

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[1] Lossen, *Zeitsch. Deutsch. Geol. Gesel.* xix. (1867), p. 573. See also *Quart. Journ. Geol. Soc.* xxxix. (1883), pp. 302, 320. Rosenbusch, 'Mikroskopische Physiographie,' ii. p. 235. F. Posepny, Tschermak's *Mineral. Mitth.* x. 175.

[2] Rothpletz, *Geol. Survey Saxony*, Explanation of Section Rochlitz.

[3] De la Vallée Poussin and Renard, *Mem. Couronnées Acad. Roy. Belg.* 1876, p. 85.

[4] Lossen, *Sitz. Gesellsch. Naturf. Freunde*, 1883, No. 9.

[5] *Q. J. Geol. Soc.* (1863), p. 401, and his address in vol. xxxvi. (1880), p. 85. The apparent current-bedding of many granulitic and other metamorphic rocks is certainly deceptive, and must be due to planes of shearing or slipping in the mechanical movements which produced the metamorphism.

correspond with original bedding, but with structural planes (cleavage, faulting) superinduced by pressure, tension, or otherwise, upon rocks which may not always have been of sedimentary origin.

Among the varieties of mica-schist may be mentioned **Sericite-schist** (which may be also included among the phyllites), composed of an aggregate of fine folia of the silky variety of mica called sericite, in a compact honestone-like quartz; **Paragonite-schist**, where the mica is the hydrous soda variety, paragonite; **Gneiss-mica-schist**, containing dispersed kernels of orthoclase. Some of these rocks contain little or no quartz, the place of which is taken by felspar. **Calc-mica-schist**, a schistose calcareous rock, which in many, if not in all cases, was originally a limestone with more or less muddy impurity. The carbonate of lime has assumed a granular-crystalline form, while the aluminous silicates have re-crystallized as fine scales of white mica. Tremolite, zoisite, and other minerals are not infrequent in this rock.

Normal mica-schist, together with other schistose rocks, forms extensive regions in Norway, Scotland, the Alps, and other parts of Europe, and vast tracts of the "Archæan" regions of North America. Some of its varieties are also found encircling granite masses (Scotland, Ireland, etc.) as a zone or aureole of contact-metamorphism from a few yards to a mile or so broad, which shades away into unaltered greywacke or slate outside. In these cases, mica-schist is unquestionably a metamorphosed condition of ordinary sedimentary strata, the change being connected with the extravasation of granite. (Book IV. Part VIII.)

Though the possession of a fissile structure, showing abundant divisional surfaces covered with glistening mica, is characteristic of mica-schist, we must distinguish between this structure and that of many micaceous sandstones which can be split into thin seams, each splendent with the sheen of its mica-flakes. A little examination will show that in the latter case the mica has not crystallized *in situ*, but exists merely in the form of detached worn scales, which, though lying on the same general plane, are not welded into each other as in a schist; also that the quartz does not exist in folia but in rounded separate grains.

13. QUARTZ- AND FELSPAR-ROCKS.—The replacement of the mica of a mica-schist by felspar, or the disappearance of the mica from a gneiss, gives rise to an aggregate of felspar and quartz. Such a rock may be observed in thin bands or courses, alternating with the surrounding mass. In mineral composition, it may be compared to the quartz-porphyries or granite-porphyries of the massive rocks, but it is usually distinguishable by a more or less foliated structure, and by the absence of felsitic ground-mass.

14. QUARTZ-, FELSPAR-, AND MICA-ROCKS.—**Gneiss.**—This name, formerly restricted to a schistose aggregate of orthoclase (sometimes microcline or a plagioclastic felspar, either separate or crystallized together), quartz, and mica, is now commonly employed in a wider sense to denote the coarser schists which so often present granitoid characters.[1] Many gneisses, indeed, differ from granite chiefly in the foliated arrangement of the minerals. The quartz sometimes contains abundant liquid inclusions, in which liquid carbon-dioxide has been detected. The relative proportions of the minerals, and the manner in which they are grouped with each other, present great variations. As a rule, the folia are coarser, and the schistose character less perfect than in mica-schist. Sometimes the quartz lies in tolerably pure bands, a foot or even more in thickness, with plates of mica scattered through it. These quartz layers may be replaced by a crystalline mixture of quartz and felspar, or the felspar will take the form of independent lenticular folia, while the laminæ of mica which lie so abundantly in the rock, give it its fissile structure. The felspar of many gneisses presents under the microscope a

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[1] See Kalkowsky's 'Gneissformation des Eulengebirges,' Leipzig, 1878; Lehmann's 'Altkrystallinische Schiefergesteine,' 1884; F. Becke, Tschermak's *Min. Mitth.* 1882, p. 194; E. Weber, *op. cit.* 1884, p. 1, and *postea* Book IV. Part VIII. § ii. and Book VI. Pre-Cambrian.

remarkable fibrous structure, due to the crystallization of fine lamellæ of some plagioclase (albite or oligoclase) in the main mass of orthoclase or microcline.[1] Among the accessory minerals, garnet, tourmaline or schorl, hornblende, apatite, graphite, pyrites, and magnetite may be enumerated.

There can be no doubt that many gneisses owe their characteristic schistose structure to the crushing and shearing of some original eruptive rock such as granite. Instances, however, occur where the materials are segregated in bands which so closely resemble those of true flow-structure or segregation in igneous bosses and sheets as to suggest that they may possibly have resulted from the movement of a still unconsolidated eruptive mass (pp. 177, 615). Analogies to such structures may be observed among ancient and modern lavas.

Many varieties of gneiss occur. Some are distinguished by peculiarities of structure or composition, as Granite-gneiss, where the schistose arrangement is so coarse as to be unrecognisable, save in a large mass of the rock; Diorite-gneiss, gabbro-gneiss, composed of the materials of a diorite or gabbro but with a coarsely schistose structure; Porphyritic gneiss or Augengneiss, in which large eye-like kernels of orthoclase or quartz are dispersed through a finer matrix and represent larger crystals or crystalline aggregates which have been broken down and dragged along by shearing movements in the rock. Other varieties are named from the occurrence in them of one or more distinguishing minerals, as Hornblende-gneiss (syenitic gneiss), in which hornblende occurs instead of or in addition to mica; Protogine-gneiss, where the ordinary mica is altered into chlorite or a talc-like substance; Sericite-gneiss, a schistose aggregate of sericite, albite, quartz, with less frequently white and black mica and a chloritic mineral;[2] Augite-gneiss, containing an augitic mineral (not of the diallage group) and potash-felspar or potash-soda-felspar or scapolite, with hornblende (which has often crystallized parallel with the augite), brown mica, more or less quartz, and also frequently with garnet, calcite, titanite, etc.;[3] Plagioclase-gneiss, with plagioclase more abundant than orthoclase, sometimes containing hornblende, sometimes augite; Cordierite-gneiss, with the bluish vitreous mineral cordierite.

The most typical gneisses occur among the so-called "Archæan rocks," of which they form the leading type, and where they probably represent original eruptive rocks. (See Book VI. Part I.) They cover considerable areas in Scandinavia, N.-W. Scotland, Bohemia, Bavaria, Erzgebirge, Moravia, Central Alps, Canada, &c. But rocks to which the name of gneiss cannot be refused appear also among the products of the metamorphism of various stratified formations. Such are the gneisses associated with many other crystalline schists among the altered Cambrian and Silurian rocks of Scotland, Norway, and New England, the altered Devonian rocks of the Taunus, and other regions, which will be described in Book IV. Part VIII. Some of these may also be eruptive granites, diorites, &c., which have undergone shearing and have acquired a schistose character.

15. QUARTZ-, FELSPAR-, AND GARNET-ROCKS.—**Granulite**[4] (Eurite-schistoide, Leptynite of French authors, Weiss-stein)—a fine-grained granular aggregate of pale reddish,

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[1] F. Becke (Tschermak's *Min. Mitth.* 1882 (iv.) p. 198) described this structure and named it *microperthite*.

[2] K. A. Lossen, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867), p. 565.

[3] The occurrence of augite as an abundant constituent of some gneisses has been made known by microscopic research. Rocks of this nature occur in Sweden (A. Stelzner, *N. Jahrb.* 1880 (ii.), p. 103), and have been fully described from Lower Austria (F. Becke, Tschermak's *Min. Mitth.* 1882 (iv.), pp. 219-365). They are likewise well developed among the oldest gneisses of the north-west of Sutherland in Scotland.

[4] Michel-Lévy has proposed to reserve the names "Leptynite" for schistose and "Granulite" for eruptive rocks. *Bull. Soc. Géol. France,* 3rd ser. ii. pp. 177, 189, iii. p. 287, iv. p. 730, vii. p. 760; Lory, *op. cit.* viii. p. 14. Scheerer, *Neues Jahrb.* 1873, p. 673. Dathe, *N. Jahrb.* 1876, p. 225; *Z. Deutsch. Geol. Ges.* 1877, p. 274 Details re-

yellowish, or white felspar with quartz and small red garnets, occasionally with kyanite, biotite, and microscopic rutile and tourmaline. The felspar, which is the predominant constituent, presents the peculiar fibrous structure referred to in the foregoing description of gneiss (microperthite, microcline), and appears seldom to be true orthoclase. The quartz is conspicuous in thin partings between thicker more felspathic bands, giving a distinctly fissile bedded character to the mass. A dark variety, interstratified with the normal rock, is distinguished by the presence of microscopic augite or diallage (Augitgranulite of Saxony). Granulite occurs in bands among the gneiss and other members of the crystalline schist series in Saxony, Bohemia, Lower Austria, the Vosges, and Central France. The term "granulite" is also employed in a structural sense to denote a rock which has been crushed down by dynamic metamorphism, and has acquired this characteristic fine granular structure. (See pp. 99, 119).

16. FELSPAR- AND MICA-ROCKS.—Rocks composed essentially of a schistose aggregate of minutely scaly mica with some felspar, quartz, andalusite, or other mineral, occur in regions of metamorphism. Cornubianite was a name proposed by Boase for a rock composed of a felspar base, with abundant mica.[1] It is found around the granite of Cornwall, of which it is a metamorphic product. By some writers this rock has been associated with the gneisses, but it is distinguished by the scarcity or absence of quartz.

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garding the great development of the granulite of Saxony (Granulitgebirge) will be found in the explanatory pamphlets published with the sheets of the Geological Survey of Saxony, especially those of sections Rochlitz, Geringswalde, and Waldheim. The history of the origin of granulite is discussed by J. Lehmann, "Untersuchungen uber die Entstehung der Altkrystall. Schiefergesteine."

[1] 'Geology of Cornwall' (1832), pp. 226, 230.

COMPOSITION OF SOME SCHISTOSE ROCKS.

	Spec. Grav.	Silica.	Alumina.	Iron, perox	Iron, protox.	Mangan. protox.	Lime.	Magnesia.	Potash.	Soda.	Water.
Clay slate. . .	2·6—2·9	54—64	13—23	0—19	0—8·5	...	0·5—9	1—9·5	1—6	0·1—3 9	0—3·9
,, alum slate .	2·42	52·28	16·64	$Fe\,S_2$ 7·74	9·96	...	1·53	1·10	7·98	(carbon) 4·37	1·40 loss
Talc-schist . .	. .	50—58	4·5—9·0	3·5—7·0	1 0	...	1·0—1·5	23·0—31·5	...	...	0—6
Chlorite-schist . .	2·7—2·9	42—55	3—14	0—4·5	9—27	0·5	0·2—1·5	8—17	0·6	0·2—1·5	4·5—11·2
Hornblende-schist .	3·0—3·1	48—50	13·3—16·4	12—27·5	4·5—9	0—0·5	0·6—12	2—2·6	0·5—1·2	1·9—2·3	...
Hornblende-rock .	2·94	49·42	18·12	5·41	9·60	...	8·65	3·16	1·27	2·57	1·80 loss
Mica-schist . .	2·77	65·13	18·16	..	5·27	0·51	0·32	2·70	2·99	0·53	$Ti\,O_2$ 1·54
Mica-gneiss . .	2·70	65—75	13—21	0—5·8	0—6	0—0·5	1—5	0·5—3·0	1·5—4·8	0·5—2·5	...
Hornblende-gneiss .	2·80	56·83	19·68	2·88	5·76	trace	1·89	3·28	3·14	2·34	$Ti\,O_2$ 0·47 $Cu\,O$ 0·09
Granulite (Leptynite)	2·66	73·47	14·86	...	3·28	...	1·62	0·67	3·95	1·80	$H_2\,O$, 0·57

BOOK III.

DYNAMICAL GEOLOGY.

DYNAMICAL GEOLOGY investigates the processes of change at present in progress upon the earth, whereby modifications are made on the structure and composition of the crust, on the relations between the interior and the surface, as shown by volcanoes, earthquakes, and other terrestrial disturbances, on the distribution of land and sea, on the outlines of the land, on the form and depth of the sea-bottom, on marine currents, and on climate. Bringing before us, in short, the whole range of geological activities, it leads us to precise notions regarding their relations to each other, and the results which they achieve. A knowledge of this branch of the subject is thus the essential groundwork of a true and fruitful acquaintance with the principles of geology. The study of the present order of nature provides a key for the interpretation of the past.

The operations considered by Dynamical Geology may be regarded as a vast cycle of change, into the investigation of which the student may break at any point, and round which he may travel, only to find himself brought back to his starting-point. It is a matter of comparatively small moment at what part of the cycle the inquiry is begun. The changes seen in action will always be found to have resulted from some that preceded, and to give place to others that follow them.

At an early time in the earth's history, anterior to any of the periods of which a record remains in the visible rocks, the chief sources of geological energy probably lay within the earth itself. The planet still retained much of its initial heat, and in all likelihood was the theatre of great chemical changes. As it cooled, and as the superficial disturbances due to internal heat and chemical action became less marked, the influence of the sun, which must always have operated, and which in early geological times may have been more effective than it afterwards became, would then stand out more clearly, giving rise to that wide circle of surface changes wherein variations of temperature and the circulation of air and water over the surface of the earth come into play.

In the pursuit of his inquiries into the past history and into the present economy of the earth, the student must needs keep his mind ever open to the reception of evidence for kinds, and especially for degrees, of action which he had not before encountered. Human experience has been too short to allow him to assume that all the causes and modes of geological change have been definitely ascertained. Besides the fact that both terrestrial and solar energy were once probably more intense than now, there may remain for future discovery evidence of former operations by heat, magnetism, chemical change, or other agency, that may explain phenomena with which geology has to deal. Of the influences, so many and profound, which the sun exerts upon our planet, we can as yet only perceive a little. Nor can we tell what other cosmical influences may have lent their aid in the revolutions of geology.

In the present state of knowledge, all the geological energy upon and within the earth must ultimately be traced back to the primeval energy of the parent nebula, or sun. There is, however, a certain propriety and convenience in distinguishing between that part of it which is due to the survival of some of the original energy of the planet, and that part which arises from the present supply of energy received day by day from the sun. In the former case, the geologist has to deal with the interior of the earth and its reaction upon the surface; in the latter, he is called upon to study the surface of the earth, and to some extent its reaction on the interior. This distinction allows of a broad treatment of the subject under two divisions:—

I. Hypogene or Plutonic Action—the changes within the earth, caused by original internal heat and by chemical action.

II. Epigene or Surface Action—the changes produced on the superficial parts of the earth, chiefly by the circulation of air and water set in motion by the sun's heat.

PART I. HYPOGENE ACTION,

An Inquiry into the Geological Changes in Progress beneath the Surface of the Earth.

In the discussion of this branch of the subject, it is useful to carry in the mind the conception of a globe still intensely hot within, radiating heat into space, and consequently contracting in bulk. Portions of molten rocks from inside are from time to time poured out at the surface. Sudden shocks are generated, by which earthquakes are propagated to and along the surface. Wide geographical areas are upraised or depressed. In the midst of these movements, the rocks of the crust are fractured, squeezed, sheared, crumpled, rendered crystalline, and even fused.

Section i. Volcanoes and Volcanic Action.[1]

§ 1. Volcanic Products.

The term volcanic action (volcanism or volcanicity) embraces all the phenomena connected with the expulsion of heated materials from the interior of the earth to the surface. Among these phenomena, some possess an evanescent character, while others leave permanent proofs of their existence. It is naturally to the latter that the geologist gives chief attention, for it is by their means that he can trace former phases of volcanic activity in regions where, for many ages, there have been no volcanic eruptions. In the operations of existing volcanoes, he can observe only superficial manifestations of volcanic action. But examining the rocks of the earth's crust, he discovers that amid the many terrestrial revolutions which geology reveals, the very roots of former volcanoes have been laid bare, displaying subterranean phases of volcanism which could not be studied in any modern volcano. Hence an acquaintance only with active volcanoes will not afford a complete knowledge of volcanic action. It must be supplemented and enlarged by an investigation of the traces of ancient volcanoes preserved in the crust of the earth. (Book IV. Part VII.)

The word "volcano" is applied to a conical hill or mountain (composed mainly or wholly of erupted materials), from the summit and often also from the sides of which, hot vapours issue, and ashes and streams of molten rock are intermittently expelled. The term "volcanic" designates all the phenomena essentially connected with one of these channels of communication between the surface and the heated interior of the globe. Yet there is good reason to believe that the active volcanoes of the present day do not afford by any means a complete type of volcanic action. The first effort in the formation of a new volcano is to establish a fissure in the earth's crust. A volcano is only one vent or group of vents established along the line of such a fissure. But in many parts of the earth, alike in the Old World and the New, there have been periods in the earth's history when the crust was rent into innumerable fissures over areas thousands of square miles in extent, and when the molten rock, instead of issuing, as it does at a modern volcano, in narrow streams from a central elevated cone, welled out from numerous small vents along the rents, and flooded enormous tracts of country without forming any mountain or conspicuous volcanic cone in the usual sense of these terms. Of these "fissure-eruptions," apart from central volcanic cones, no examples appear to have occurred within the times of human history, except in Iceland where vast lava-floods issued from a fissure in 1783 (pp. 222, 256). They can best be studied from the remains of former convulsions. Their importance, however, has not yet been generally recognised in Europe, though acknowledged in America, where they have been largely developed. Much still remains to be done before their mechanism is as well understood as that of the lesser type to which all present volcanic action belongs. In the succeeding narrative an account is first presented of the ordinary and familiar volcano and its products; and in § 3, ii., some details are given of the general aspect and character of fissure-eruptions.

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[1] The student is referred to the following general works on the phenomena of volcanoes. Scrope, 'Considerations on Volcanoes,' London, 1825; 'Volcanoes,' London, 2nd edit. 1872; 'Extinct Volcanoes of Central France,' London, 1858; 'On Volcanic Cones and Craters,' *Quart. Journ. Geol. Soc.* 1859. Daubeny, 'A Description of Active and Extinct Volcanoes,' 2nd edit., London, 1858. Darwin, 'Geological Observations on Volcanic Islands,' 2nd edit., London, 1876. A. von Humboldt, 'Ueber den Bau und die Wirkung der Vulkane,' Berlin, 1824. L. von Buch, 'Ueber die Natur der vulkanischen Erscheinungen auf den Canarischen Inseln,' *Poggend. Annalen* (1827), ix. x.; 'Ueber Erhebungskratere und Vulkane,' *Poggend. Annalen* (1836), xxxvii. E. A. von Hoff, 'Geschichte der durch Ueberlieferung nachgewiesenen naturlichen Veränderungen der Erdoberfläche' (part ii., "Vulkane und Erdbeben"), Gotha, 1824. C. W. C. Fuchs, 'Die vulkanischen Erscheinungen der Erde,' Leipzig, 1865. R. Mallet, "On Volcanic Energy," *Phil. Trans.* 1873. J. Schmidt, 'Vulkanstudien,' Leipzig, 1874. Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna,' 4to, Leipzig, 1880. E. Reyer, 'Beitrag zur Physik der Eruptionen,' Vienna, 1877; 'Die Euganeen; Bau und Geschichte eines Vulkanes,' Vienna, 1877. Fouqué, 'Santorin et ses éruptions,' Paris, 1879. Judd, 'Volcanoes,' 1881. G. Mercalli, 'Vulcani e Fenomeni vulcanici in Italia,' Milan, 1883. Ch. Vélain, 'Les Volcans,' Paris, 1884. J. D. Dana, 'Characteristics of Volcanoes,' 1890. 'Volcanoes Past and Present,' E. Hull, 1892. 'The South Italian Volcanoes,' H. J. Johnston-Lavis, Naples 1891. References will be found in succeeding pages to other and more special memoirs.

The openings by which heated materials from the interior now reach the surface include volcanoes (with their various associated orifices) and hot-springs.

The prevailing conical form of a volcano is that which the ejected materials naturally assume round the vent of eruption. The summit of the cone is truncated (Figs. 39, 45), and presents a cup-shaped or caldron-like cavity, termed the crater, at the bottom of which is the top of the main funnel or pipe of communication with the heated interior. A volcano, when of small size, may consist merely of one cone; when of the largest dimensions, it forms a huge mountain, with many subsidiary cones and many lateral fissures or pipes, from which the heated volcanic products are given out. Mount Etna (Fig. 39), rising from the sea to a height of 10,840 feet, and supporting, as it does, some 200 minor cones, many of which are in themselves considerable hills, is a magnificent example of a colossal volcano.[1]

The materials erupted from volcanic vents may be classed as (1) gases and vapours, (2) water, (3) lava, (4) fragmentary substances. A brief summary under each of these heads may be given here; the share taken by the several products in the phenomena of an active volcano is described in § 2.

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[1] The structure and history of Etna are fully described in the great work of Sartorius von Waltershausen and A. von Lasaulx cited on p. 191—a treasure-house of facts in volcanic geology. See also G. F. Rodwell, 'Etna, a history of the mountain and its eruptions,' London, 1878; O. Silvestri, 'Un Viaggio all' Etna,' 1879. Notices of recent eruptions of the mountain will be found in *Nature*, vols. xix., xx., xxi., xxii., xxv. (observatory on Etna, p. 394), xxvii., xlvi.; *Compt. rend.* lxvi. The work of Mercalli, cited on p. 191, gives descriptions of this and the other Italian volcanic centres.

1. **Gases and Vapours** exist dissolved in the molten magma within the earth's crust. They play an important part in volcanic activity, showing themselves in the earliest stages of a volcano's history, and continuing to appear for centuries after all other subterranean action

Fig. 39.—View of Etna from the Torre Archirafi (Sartorius von Waltershausen).

has ceased. By much the most abundant of them all is water-gas, which, ultimately escaping as steam, has been estimated to form $\frac{999}{1000}$ths of the whole cloud that hangs over an active volcano (Fig. 40). In great eruptions, steam rises in prodigious quantities, and is rapidly condensed into a heavy rainfall. M. Fouqué calculated that, during 100 days, one of the parasitic cones on Etna had ejected vapour enough to form, if condensed, 2,100,000 cubic mètres (462,000,000 gallons) of water. But even from volcanoes which, like the Solfatara of Naples, have been dormant for centuries, steam sometimes still rises without intermission and in considerable volume. Jets of vapour rush out from clefts in the sides and bottom of a crater with a noise like that made by the steam blown off by a locomotive. The number of these funnels or "fumaroles" is often so large, and the amount of vapour so abundant, that only now and then, when the wind blows the dense cloud aside, can a momentary glimpse be had of a part of the bottom of the crater; while at the same time the rush and roar of the escaping steam remind one of the din of some vast factory. Aqueous vapour rises likewise from rents on the outside of the volcanic cone. It issues so copiously from some flowing lavas that the stream of rock may be almost concealed from view by the cloud; and it continues to escape from fissures of the lava, far below the point of exit, for a long time after the rock has solidified and come to rest. So saturated are many molten lavas with water-vapour that Mr. Scrope thought that they owed their mobility to this cause.[1] In the deep volcanic magma the water-substance must be far above its critical temperature, which is about 773° Fahr.

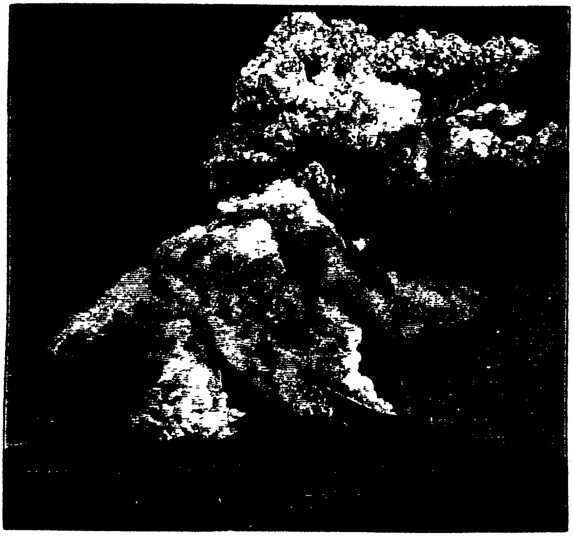

Fig. 40.—View of Vesuvius as seen from Naples during the eruption of 1872, showing the dense clouds of condensed aqueous vapour.

Probably in no case is the steam mere pure vapour of water, though when it condenses into copious rain, it is fresh and not salt water. It is associated with other vapours and gases disengaged from the potent chemical laboratory underneath. There seems to be always a definite order in the appearance of these vapours, though it may vary for different volcanoes. The hottest and most active "fumaroles," or vapour-vents, may contain all the gases and vapours of a volcano, but as the heat diminishes, the series of gaseous emanations is reduced. Thus in the Vesuvian eruption of 1855-56, the lava, as it cooled and hardened, gave out successively vapours of hydrochloric acid, chlorides, and sulphurous acid; then steam; and, finally, carbon-dioxide and combustible gases.[1] More recent observations tend to corroborate the deductions of C. Sainte-Claire Deville that the nature of the vapours evolved depends on the temperature or degree of activity of the volcanic orifice, chlorine (and fluorine) emanations indicating the most energetic phase of eruptivity, sulphurous gases a diminishing condition, and carbonic acid (with hydrocarbons) the dying out of the activity.[2] A "solfatara," or vent emitting only gaseous discharges, is believed to pass through these successive stages. Wolf observed that on Cotopaxi while hydrochloric acid, and even free chlorine escaped from the summit of the cone, sulphuretted hydrogen and sulphurous acid issued from the middle and lower slopes.[3] Fouqué's studies at Santorin have shown also that from submarine vents a similar order of appearance obtains among the volcanic vapours, hydrochloric and sulphurous acids being only found at points of emission having a temperature above 100° C., while carbon-dioxide, sulphuretted hydrogen, and nitrogen occur at all the fumaroles, even where the temperature is not higher than that of the atmosphere.[4]

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[1] 'Considerations on Volcanoes' (1825), p. 110.

The following are the chief gases and acids evolved at volcanic fumaroles. Hydrochloric acid is abundant at Vesuvius, and probably at many other vents whence it has not been recorded. It is recognisable by its pungent, suffocating fumes, which make approach difficult to the clefts from which it issues. Sulphuretted hydrogen and sulphurous acid are distinguishable by their odours. The liability of the former gas to decomposition leads to the deposition of a yellow crust of sulphur; occasionally, also, the production of sulphuric acid is observed at active vents. From observations made at Vesuvius in May 1878, Mr. Siemens concluded that vast quantities of free hydrogen or of combustible compounds of this gas exist dissolved in the magma of the earth's interior, and that these, rising and exploding in the funnels of volcanoes, give rise to the detonations and clouds of steam.[1] At the eruption of Santorin in 1866, the same gases were also distinctly recognised by Fouqué, who for the first time established the existence of true volcanic flames. These were again studied spectroscopically in the following year by Janssen, who found them to arise essentially from the combustion of free hydrogen, but with traces of chlorine, soda, and copper. Fouqué determined by analysis that, immediately over the focus of eruption, free hydrogen formed thirty per cent of the gases emitted, but that the proportion of this gas rapidly diminished with distance from the active vents and hotter lavas, while at the same time the proportion of marsh-gas and carbon-dioxide rapidly increased. The gaseous emanations collected by him were found to contain abundant free oxygen as well as hydrogen. One analysis gave the following results: carbon-dioxide 0·22, oxygen 21·11, nitrogen 21·90, hydrogen 56·70, marsh-gas 0·07, = 100·00. This gaseous mixture, on coming in contact with a burning body, at once ignites with a sharp explosion. Fouqué infers that the water-vapour of volcanic vents may exist in a state of dissociation within the molten magma whence lavas rise.[2] Carbon-dioxide rises chiefly (*a*) after an eruption has ceased and the volcano relapses into quiescence; or (*b*) after volcanic action has otherwise become extinct. Of the former phase, instances are on record at Vesuvius where an eruption has been followed by the emission of this gas so copiously from the ground as to suffocate hundreds of hares, pheasants, and partridges. Of the second phase, good examples are supplied by the ancient volcanic regions of the Eifel and Auvergne, where the gas still rises in prodigious quantities. Bischof estimated that the volume of carbonic acid evolved in the Brohl Thal amounts to 5,000,000 cubic feet, or 300 tons of gas in one day. Nitrogen, derived perhaps from the decomposition of atmospheric air dissolved in the water which penetrates into the volcanic foci, has been frequently detected among the gaseous emanations. At Santorin it was found to form from 4 to 88 per cent of the gas obtained from different fumaroles[3] Fluorine and iodine have likewise been noticed.

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[1] C. Sainte-Claire Deville and Leblanc, *Ann. Chim. et Phys.*, 1858, lii. p. 19 *et seq.* For accounts of Vesuvius and its eruptions, besides the general works already cited on p. 191, consult J. Phillips' 'Vesuvius,' 1869; 'Mount Vesuvius,' J. L. Lobley, 1889; J. Schmidt, 'Die Eruption des Vesuv. 1855,' Vienna, 1856; Mercalli's 'Vulcani, &c.'; H. J. Johnston-Lavis, *Q. J. Geol. Soc.* xl. 35; *Geol. Mag.* 1888, p. 445. A diary of the volcano's behaviour for six months is given in *Nature*, xxvi.; one for four years (1882-1886) by Dr. Johnston-Lavis 'Spettatore del Vesuvio,' Naples, 1887; a valuable series of reports on the mountain by the same author will be found in recent volumes of the *Reports of the British Association* (1885-91) and a large detailed map of the volcano, also by him, published by Philip, London, 1891.

[2] He distinguished volcanic emanations according to their order of appearance as regards time, nearness to the vent, and temperature: viz., 1. Dry fumaroles (without steam), where anhydrous chlorides are almost the only discharge, and where the temperature is very high (above that of melted zinc). 2. Acid fumaroles, with sulphurous and hydrochloric acids and steam. 3. Alkaline (ammoniacal) fumaroles; temperature about 100° C.; abundant steam with chloride of ammonium. 4. Cold fumaroles; temperature below 100° C., with nearly pure steam, accompanied by a little carbon-dioxide, and sometimes sulphuretted hydrogen. 5. Mofettes; emanations of carbon-dioxide with nitrogen and oxygen, marking the last phase of volcanic activity.

[3] *Neues Jahrb.* 1878, p. 164.

[4] 'Santorin et ses éruptions,' Paris, 1879.

With these gases and vapours are associated many substances which, sublimed by the volcanic heat or resulting from reactions among the escaping vapours, appear as Sublimates along crevices wherein they reach the air and are cooled. Besides sulphur, there are several chlorides (particularly that of sodium, and less abundantly those of potassium, iron, copper, and lead); also free sulphuric acid, salammoniac, specular iron, oxide of copper, boracic acid, alum, sulphate of lime, felspars, pyroxene, and other substances. Carbonate of soda occurs in large quantities among the fumaroles of Etna. Sodium-chloride sometimes appears so abundantly that wide spaces of a volcanic cone, as well as of the newly-erupted lava, are crusted with salt, which can even be profitably removed by the inhabitants of the district. Considerable quantities of chlorides, &c., may thus be buried between successive sheets of lava, and in long subsequent times, may give rise to mineral springs, as has been suggested with reference to the saline waters which issue from volcanic rocks of Old Red Sandstone and Carboniferous age in Scotland.[4] The iron-chloride forms a bright yellow and reddish crust on the crater walls, as well as on loose stones on the slopes of the cone. Specular iron, from the decomposition of iron-chloride, forms abundantly as thin lamellæ in the fissures of Vesuvian lavas. In the spring of 1873 the author observed delicate brown filaments of tenorite (copper-oxide, CuO) forming in clefts of the crater of Vesuvius. They were upheld by the upstreaming current of vapour until blown off by the wind. Fouqué has described tubular vents in the lavas of Santorin with crystals of anorthite, sphene, and pyroxene, formed by sublimation. In the lava stalactites of Hawaii needle-like fibres of breislakite abound.

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[1] *Monatsb. K. Preuss. Akad.* 1878, p. 588.

[2] Fouqué, 'Santorin et ses éruptions,' p. 225.

[3] Fouqué, *loc. cit.*

[4] *Proc. Roy. Soc. Edin.* ix. p. 367.

2. **Water.**—Abundant discharges of water accompany some volcanic explosions. Three sources of this water may be assigned:—(1) from the melting of snow by a rapid accession of temperature previous to or during an eruption; this takes place from time to time on Etna, in Iceland, and among the snowy ranges of the Andes, where the cone of Cotopaxi is said to have been entirely divested of its snow in a single night by the heating of the mountain; (2) from the condensation of the vast clouds of steam which are discharged during an eruption; this undoubtedly is the chief source of the destructive torrents so frequently observed to form part of the phenomena of a great volcanic explosion; and (3) from the disruption of reservoirs of water filling subterranean cavities, or of lakes occupying crater-basins; this has several times been observed among the South American volcanoes, where immense quantities of dead fish, which inhabited the water, have been swept down with the escaping torrents. The volcano of Agua in Guatemala, received its name from the disruption of a crater-lake at its summit by an earthquake in 1540, whereby a vast and destructive debacle of water was discharged down the slopes of the mountain.[1] In the beginning of the year 1817, an eruption took place at the large crater of Idjèn, one of the volcanoes of Java, whereby a steaming lake of hot acid water was discharged with frightful destruction down the slopes of the mountain. After the explosion, the basin filled again with water, but its temperature was no longer high.[2]

In many cases, the water rapidly collects volcanic dust as it rushes down, and soon becomes a pasty mud; or it issues at first in this condition from the volcanic reservoirs after violent detonations. Hence arise what are termed mud-lavas, or aqueous lavas, which in many respects behave like true lavas. This volcanic mud eventually consolidates into one of the numerous forms of tuff, a rock which, as has been already stated (p. 135), varies greatly in the amount of its coherence, in its composition, and in its internal arrangement. Obviously, unless where subsequently altered, it cannot possess a crystalline structure like that of true lava. As a rule, it betrays its aqueous origin by more or less distinct evidence of stratification, by the multifarious pebbles, stones, blocks of rock, tree-trunks, branches, shells, bones, skeletons, &c., which it has swept along in its course and preserved within its mass. Sections of this compacted tuff may be seen at Herculaneum.[3] The *trass* of the Brohl Thal and other valleys in the

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[1] For an account of this mountain see K. v. Seebach, *Abh. Gesell. Wiss. Göttingen*, xxxviii. (1892) p. 216.

[2] See Junghuhn's 'Java.' For an account of the volcanoes of the Sunda Island and Moluccas, see F. Scheider, *Jahrb. Geol. Reichsanst.* Vienna, xxxv. (1885), p. 1. Consult also for the Javanese volcanoes the works on Krakatoa quoted on p. 212.

[3] Mallet thought that the so-called "mud-lavas" of Herculaneum and Pompeii were not aqueous deposits (*Journ. Roy. Geol. Soc. Ireland*, IV. (1876), p. 144). But there seems no reason to doubt that while an enormous amount of ashes fell during the eruption of A.D. 79,

Eifel district, referred to on p. 137, is another example of an ancient volcanic mud.

3. Lava.—The term lava is applied generally to all the molten rocks of volcanoes.[1] The use of the word in this broad sense is of great convenience in geological descriptions, by directing attention to the leading character of the rocks as molten products of volcanic action, and obviating the confusion and errors which are apt to arise from an ill-defined or incorrect lithological terminology. Precise definitions of the rocks, such as those above given in Book II., can be added when required. A few remarks regarding some of the general lithological characters of lavas may be of service here; the behaviour of the rocks in their emission from volcanic orifices will be described in § 2.

While still flowing or not yet cooled, lavas differ from each other in the extent to which they are impregnated with gases and vapours. Some appear to be saturated, others contain a much smaller gaseous impregnation; and hence arise important distinctions in their behaviour (pp. 217-231). After solidification, lavas present some noticeable characters, then easily ascertainable. (1) Their average specific gravity may be taken as ranging between 2·37 and 3·22. (2) The heavier varieties contain much magnetic or titaniferous iron, with augite and olivine, their composition being basic, and their proportion of silica averaging about 45 to 55 per cent. In this group come the basalts, nepheline-lavas, and leucite-lavas. The lighter varieties contain commonly a minor proportion of metallic bases, but are rich in silica, their percentage of that acid ranging between 70 and 75. They are thus not basic but acid rocks. Among their more important varieties are the rhyolites and obsidians. Some intermediate varieties (trachytes, phonolites, and andesites) connect the acid and basic series. (3) Lavas differ much in structure and texture. (*a*) Some are entirely crystalline, consisting of an interlaced mass of crystals and crystalline particles, as in some dolerites, and granitoid rhyolites. Even quartz, which used to be considered a non-volcanic mineral, characteristic of the older and chiefly of the plutonic eruptive rocks, has been observed in large crystals in modern lava (liparite and quartz-andesite[2]). (*b*) Some show more or less of a half-glassy or stony (devitrified) matrix, in which the constituent crystals are imbedded; this is the most common arrangement. (*c*) Others are entirely vitreous, such crystals or crystalline particles as occur in them being quite subordinate, and, so to speak, accidental enclosures in the main glassy mass. Obsidian or volcanic glass is the type of this group. (*d*) They further differ in the extent to which minute pores or larger cellular spaces have been developed in them. According to Bischof, the porosity of lavas depends on their degree of liquidity, a porous lava or slag, when reduced in his fusion-experiments to a thin-flowing consistency, hardening into a mass as compact as the densest lava or basalt.[3] The presence of interstitial steam in lavas, by expanding

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there were likewise, especially in the later phases of eruption, copious torrents of water that mingled with the fine ash and became "mud-lavas." The sharpness of outline and the absence of any trace of abdominal distension in the moulds of the human bodies found at Pompeii, probably show that these victims of the catastrophe were rapidly enveloped in a firm coherent matrix which could hardly have been mere loose dust. See H. J. Johnston-Lavis, *Q. J. Geol. Soc.* xl. p. 89.

[1] "Alles ist Lava was im Vulkane fliesst und durch seine Flüssigkeit neue Lagerstätter einnimmt" is Leopold von Buch's comprehensive definition.

[2] Wolf, *Neues Jahrb.* 1874, p. 377.

[3] 'Chem. und Phys. Geol.' supp. (1871), p. 144. On the production of the vesicular

the still molten stone, produces an open cellular texture, somewhat like that of sponge or of bread. Such a vesicular arrangement very commonly appears on the upper surface of a lava current, which assumes a slaggy or cindery aspect. In some forms of pumice the proportion of air cavities is 8 or 9 times that of the enclosing glass. (4) Lavas vary greatly in colour and general external aspect. The heavy basic kinds are usually dark grey, or almost black, though, on exposure to the weather, they acquire a brown tint from the oxidation and hydration of their iron. Their surface is commonly rough and ragged, until it has been sufficiently decomposed by the atmosphere to crumble into soil which, under favourable circumstances, supports a luxuriant vegetation. The less dense lavas, such as phonolites and trachytes, are frequently paler in colour, sometimes yellow or buff, and decompose into light soils; but the obsidians present rugged black sheets of rock, roughened with ridges and heaps of grey froth-like pumice. Some of the most brilliant surfaces of colour in any rock-scenery on the globe are to be found among volcanic rocks. The walls of active craters glow with endless hues of red and yellow. The Grand Cañon of the Yellowstone River has been dug out of the most marvellously tinted lavas and tuffs.

4. **Fragmentary Materials.**—Under this title may be included all the substances which, driven up into the air by volcanic explosions, fall in solid form to the ground—the dust, ashes, sand, cinders, and blocks of every kind which are projected from a volcanic orifice. These materials differ in composition, texture, and appearance, even during a single eruption, and still more in successive explosions of the same volcano. For the sake of convenience, separate names are applied to some of the more distinct varieties, of which the following may be enumerated.

(1) Ashes and sand.—In many eruptions, vast quantities of an exceedingly fine light grey powder are ejected. As this substance greatly resembles what is left after a piece of wood or coal is burnt in an open fire, it has been popularly termed *ash*, and this name has been adopted by geologists. If, however, by the word ash, the result of combustion is implied, its employment to denote any product of volcanic action must be regretted, as apt to convey a wrong impression. The fine ash-like dust ejected by a volcano is merely lava in an extremely fine state of comminution. So minute are the particles that they find their way readily through the finest chinks of a closed room, and settle down upon floor and furniture, as ordinary dust does when a house is shut up. From this finest form of material, gradations may be traced, through what is termed volcanic sand, into the coarser varieties of ejected matter. In composition, the ash and sand vary necessarily with the nature of the lava from which they are derived. Their microscopic structure, and especially their abundant microlites, crystals, and volcanic glass, have been already referred to (pp. 136, 137).

(2) Lapilli or rapilli (p. 136) are ejected fragments ranging from the size of a pea to that of a walnut; round, subangular, or angular in shape, and having the same indefinite range of composition as the finer dust. As a rule, the larger pieces fall nearest the focus of eruption. Sometimes they are solid fragments of lava, but more usually they have a cellular texture, while sometimes they are so light and porous as to float readily on water, and, when ejected near the sea, to cover its surface. Well-formed crystals occur in the lapilli of many volcanoes, and are also ejected separately. It has been observed indeed that the fragmentary materials not infrequently contain finer crystals than the accompanying lava.[1]

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structure consult Dana, 'Characteristics of Volcanoes,' p. 161. Compare also Judd, *Geol. Mag.* 1888, p. 7.

[1] Sartorius von Waltershausen, 'Sicilien und Island,' 1853, p. 328.

(3) **Volcanic Blocks** (p. 136) are larger pieces of stone, often angular in shape. In some cases they appear to be fragments loosened from already solidified rocks in the chimney of the volcano. Hence we find among them pieces of non-volcanic rocks, as well as of older tuffs and lavas recognisably belonging to early eruptions. In many cases, they are ejected in enormous quantities during the earlier phases of violent eruption. The great explosion from the side of Ararat in 1840 was accompanied by the discharge of a vast quantity of fragments over a space of many square miles around the mountain. Whitney has described the occurrence in California of beds of such fragmentary volcanic breccia, hundreds of feet thick and covering many square miles of surface. Junghuhn, in his account of the eruption in Java in 1772, mentions that a valley ten miles long was filled to an average depth of fifty feet with angular volcanic débris.[1]

Among the earlier eruptions of a volcano, fragments of the rocks through which the vent has been drilled may frequently be observed. These are in many cases not volcanic. Blocks of schist and granitoid rocks occur in the cinder-beds at the base of the volcanic series of Santorin. In the older tuffs of Somma, pieces of altered limestone (sometimes measuring 200 cubic feet or more and weighing upwards of 15 tons) are abundant and often contain cavities lined with the characteristic "Vesuvian minerals."[2] Blocks of a coarsely crystalline granitoid (but really trachytic) lava have been particularly observed both on Etna[3] and Vesuvius. In the year 1870 a mass of that kind, weighing several tons, was to be seen lying at the foot of the upper cone of Vesuvius, within the entrance to the Atrio del Cavallo. Similar blocks occur among the Carboniferous volcanic pipes of central Scotland, together sometimes with fragments of sandstone, shale, or limestone, not infrequently full of Carboniferous fossils.[4] Enormous masses of various schists have been carried up by the lavas of the Tertiary volcanic plateau of the Inner Hebrides.[5]

(4) **Volcanic Bombs and slags.**—These have originally formed portions of the column of lava ascending the pipe of a volcano, and have been detached and hurled into the air by successive explosions of steam. A **bomb** (Fig. 41) is a round,

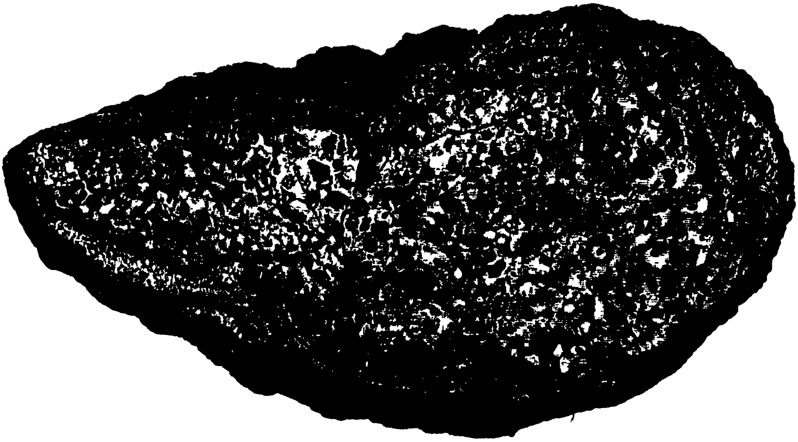

Fig. 41.—Section of Volcanic Bomb, one-third natural size.

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[1] But see the remarks already made on volcanic conglomerates, *ante*, p. 136.

[2] See H. J. Johnston-Lavis, *Q. J. Geol. Soc.* xl. p. 75.

[3] For the erupted blocks (Auswurflinge) of Etna see 'Der Aetna,' ii. pp. 216, 330, 461.

[4] *Trans. Roy. Soc. Edin.* xxix. p. 459. See *postea*, Book IV. Sect. vii. § 1, 4.

[5] *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 82.

elliptical, or pear-shaped, often discoidal mass of lava, from a few inches to several feet in diameter; sometimes tolerably solid throughout, more usually coarsely cellular inside. Not infrequently its interior is hollow, and the bomb then consists of a shell which is most close-grained towards the outside, or the centre is a block of stone with an external coating of lava. There can be no doubt that, when torn by eructations of steam from the surface of the boiling lava, the material of these bombs is in as thoroughly molten a condition as the rest of the mass. From the rotatory motion imparted by its ejection, it takes a circular form, and in proportion to its rapidity of rotation and fluidity is the amount of its "flattening at the poles." The centrifugal force within allows the expansion of the interstitial vapour, while the outer surface rapidly cools and solidifies; hence the solid crust, and the porous or cavernous interior. Such bombs, varying from the size of an apple to that of a man's body, were found by Darwin abundantly strewn over the ground in the Island of Ascension; they were also ejected in vast quantities during the eruption of Santorin in 1866.[1] Among the tuffs of the Eifel region, small bombs, consisting mostly of granular olivine, are of common occurrence, as also pieces of sanidine or other less fusible minerals which have segregated out of the magma before ejection. In like manner, among the tuffs filling volcanic necks, probably of Permian age, which pierce the Carboniferous rocks of Fife, large worn crystals of orthoclase, biotite, &c., are found. When the ejected fragment of lava has a rough irregular form and a porous structure, like the clinker of an iron-furnace, it is known as a slag.[2]

The fragmentary materials erupted by a volcano and deposited around it acquire by degrees more or less consolidation, partly from the mere pressure of the higher upon the lower strata, partly from the influence of infiltrating water. It has been already stated (p. 136) that different names are applied to the rocks thus formed. The coarse, tumultuous, unstratified accumulation of volcanic débris within a crater or funnel is called Agglomerate. When the débris, though still coarse, is more rounded, and is arranged in a stratified form on the slopes of the cone or on the country beyond, it becomes a Volcanic Conglomerate. The finer-grained varieties, formed of dust and lapilli, are included in the general designation of Tuffs. These are usually pale yellowish, greyish, or brownish, sometimes black rocks, granular, porous, and often incoherent in texture. They occur interstratified with and pass into ordinary non-volcanic sediment.

Organic remains sometimes occur in tuff. Where volcanic débris has accumulated over the floor of a lake, or of the sea, the entombing and preserving of shells and other organic objects must continually take place. Examples of this kind are cited in later pages of this volume from older geological formations. Professor Guiscardi of Naples found about 100 species of marine shells of living species in the old tuffs of Vesuvius. Marine shells have been picked up within the crater of Monte Nuovo, and have been frequently observed in the old or marine tuff of that district. Showers of ash, or sheets of volcanic mud, often preserve land-shells, insects, and vegetation living on the area at the time. The older tuffs of Vesuvius have yielded many remains of the shrubs and trees which at successive periods have clothed the flanks of the mountain. Fragments of coniferous wood, which once grew on the tuff-cones of Carboniferous age in central Scotland, are abundant in the "necks" of that region, while the minute structure of some of the lepidodendroid plants has also been admirably preserved there in tuff.[3]

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[1] Darwin, 'Geological Observations on Volcanic Islands,' 2nd edit. p. 42. Fouqué, 'Santorin,' p. 79.

[2] On the ratio between the pores and volume of the rock in slags and lavas, see determinations by Bischof, 'Chem. und Phys. Geol.' supp. (1871), p. 158.

[3] *Trans. Roy. Soc. Edin.* xxix. p. 470; *postea*, Book IV. Part VII. Sect. ii. § 2.

§ 2. Volcanic Action.

Volcanic action may be either constant or periodic. Stromboli, in the Mediterranean, so far as we know, has been uninterruptedly emitting hot stones and steam, from a basin of molten lava, since the earliest period of history.[1] Among the Moluccas, the volcano Sioa, and in the Friendly Islands, that of Tofua, have never ceased to be in eruption since their first discovery. The lofty cone of Sangay, among the Andes of Quito, is always giving off hot vapours; Cotopaxi, too, is ever constantly active.[2] But, though examples of unceasing action may thus be cited from widely different quarters of the globe, they are nevertheless exceptional. The general rule is that a volcano breaks out from time to time with varying vigour, and after longer or shorter intervals of quiescence.

Active, Dormant, and Extinct Phases.—It is usual to class volcanoes as *active*, *dormant*, and *extinct*. This arrangement, however, often presents considerable difficulty in its application. An active volcano cannot of course be mistaken, for even when not in eruption, it shows by its discharge of steam and hot vapours that it might break out into activity at any moment. But in many cases, it is impossible to decide whether a volcano should be called extinct or only dormant. The volcanoes of Silurian age in Wales, of Carboniferous age in Ireland, of Permian age in the Harz, of Miocene age in the Hebrides, of younger Tertiary age in the Western States and Territories of North America, are certainly all extinct. But the older Tertiary volcanoes of Iceland are still represented there by Skaptar-Jökull, Hecla, and their neighbours.[3] Somma, in the first century of the Christian era, would have been naturally regarded as an extinct volcano. Its fires had never been known to have been kindled; its vast crater was a wilderness of wild vines and brushwood, haunted, no doubt, by wolf and wild boar. Yet in a few days, during the autumn of the year 79, the half of the crater walls was blown out by a terrific series of explosions, the present Vesuvius was then formed within the limits of the earlier crater, and since that time volcanic action has been intermittently exhibited up to the present day. Some of the intervals of quietude, however, have been so considerable that the mountain might then again have been claimed as an extinct volcano. Thus, in the 131 years between 1500 and 1631, so completely had eruptions ceased that the crater had once more become choked with copsewood. A few pools and springs of very salt and hot water remained as memorials of the former condition of the mountain. But this period of quiescence closed with the eruption of 1631,—the most powerful of all the known explosions of Vesuvius, except the great one of 79. In the island of Ischia, Mont' Epomeo was last in eruption in the year 1302, its previous outburst having taken place, it is believed, about seventeen centuries before that date. From the craters of the Eifel, Auvergne, the Vivarais, and central Italy, though many of them look as if they had only recently been formed, no eruption has been known to come during the times of human history or tradition. In the west of North America, from Arizona to Oregon, numerous stupendous volcanic cones occur, but even from the most perfect and fresh of them nothing but steam and hot vapours has yet been known to proceed.[1] But the presence there of hot springs and geysers proves the continued existence of one phase of volcanic action.

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[1] For accounts of Stromboli see Spallanzani's 'Voyages dans les deux Siciles.' Scrope's 'Volcanoes' Judd, *Geol. Mag.* 1875. Mercalli's 'Vulcani, &c.' p. 135; and his papers in *Atti Soc. Ital. Sci. Nat.* xxii. xxiv. xxvii. xxix. xxxi. L. W. Fulcher, *Geol. Mag.* 1890, p. 347.

[2] For descriptions of Cotopaxi, see Wolf, *Neues Jahrb.* 1878; Whymper, *Nature*, xxiii. p. 323; 'Travels amongst the Great Andes,' chap. vi.

[3] On the volcanic phenomena of Iceland consult G. Mackenzie's 'Travels in the Island of Iceland during the Summer of 1810.' E. Henderson's 'Iceland.' Zirkel, 'De geognostica Islandæ constitutione observationes,' Bonn, 1861. Thoroddsen, 'Oversigt over de islandske Vulkaners Historie,' translated in resumé by G. H. Boehmer, *Smithsonian Inst. Rep.* 1885, part i. p. 495; also *Bihang t. Svensk. Vet. Akad. Handl.* 14, ii. (1888), 17, ii. (1891); *Geol. Mag.* 1880, p. 458; *Nature*, Oct. 1884. *Mitth. K. K. Geogr. Ges.* Vienna, xxiv. (1891), p. 117. Keilhack, *Zeitsch. Deutsch. Geol. Gesel.* xxxviii. (1886), p. 376; Schmidt, *op. cit.* xxxvii. (1885), p. 737; A. Helland, 'Lakis Kratere og Lava-strome,' *Universitets Programme*, Christiania, 1885; Bréon, 'Géologie de l'Islande, et des Isles Foeroe,' Paris, 1884; T. Anderson, *Journ. Soc. Arts*, vol. xl. (1892), p. 397.

In short, no essential distinction can be drawn between dormant and extinct volcanoes. Volcanic action, as will be afterwards pointed out, is apt to show itself again and again, even at vast intervals, within the same regions and over the same sites. The dormant or waning condition of a volcano, when only steam and various gases and sublimates are given off, is sometimes called the Solfatara phase, from the well-known dormant crater of that name near Naples.

Sites of Volcanic Action.—Volcanoes may break through any geological formation. In Auvergne, in the Miocene period, they burst through the granitic and gneissose plateau of central France. In Lower Old Red Sandstone times, they pierced contorted Silurian rocks in central Scotland. In late Tertiary and post-Tertiary ages, they found their way through recent soft marine strata, and formed the huge piles of Etna, Somma, and Vesuvius; while in North America, during the same cycle of geological time, they flooded with lava and tuff many of the river-courses, valleys, and lakes of Nevada, Utah, Wyoming, Idaho, and adjacent territories. On the banks of the Rhine, at Bonn and elsewhere, they have penetrated some of the older alluvia of that river. In many instances, also, newer volcanoes have appeared on the sites of older ones. In Scotland, the Carboniferous volcanoes have risen on the ruins of those of the Old Red Sandstone, those of the Permian period have broken out among the earlier Carboniferous eruptions, while the older Tertiary dykes have been injected into all these older volcanic masses. The newer *puys* of Auvergne were sometimes erupted through much older and already greatly denuded basalt-streams. Somma and Vesuvius have risen out of the great Neapolitan plain of older marine tuff, while in central Italy, newer cones have been thrown up upon the wide Roman plain of more ancient volcanic débris.[2] The vast Snake River lava-fields of Idaho overlie denuded masses of earlier trachytic lavas, and similar proofs of a long succession of intermittent and widely-separated volcanic outbursts can be traced northwards into the Yellowstone Valley.

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[1] Eruptions occurred perhaps less than 100 years ago. Diller, *Bull. U. S. Geol. Surv.*, No. 79.

[2] According to Professor G. Pozzi, the principal volcanic outbursts of Italy are of

When a volcanic vent is opened, it might be supposed always to find its way to the surface along some line of fissure, valley, or deep depression. No doubt many, if not most, modern as well as ancient vents, especially those of large size, have done so. It is a curious fact, however, that in innumerable instances minor vents have appeared where there was no visible line of dislocation in the rocks at the surface to aid them. This has been well shown by a study of the ancient volcanic rocks of the Old Red Sandstone, Carboniferous, and Permian formations of Scotland.[1] It has likewise been most impressively demonstrated by the way in which the minor basalt cones and craters of Utah have broken out near the edges or even from the face of cliffs, rather than at the bottom. Captain Dutton remarks that among the high plateaux of Utah, where there are hundreds of basaltic craters, the least common place for them is at the base of a cliff, and that, though they occur near faults, it is almost always on the lifted, rarely upon the depressed side.[2] On a small scale, a similar avoidance of the valley bottom is shown on the Rhine and Moselle, where eruptions have taken place close to the edge of the plateau through which these rivers wind. Why outbreaks should have occurred in this way is a question not easily answered. It suggests that the existing depressions and heights of the earth's surface may sometimes be insignificant features, compared with the depth of the sources of volcanoes and the force employed in volcanic eruption. On the other hand, it is remarkable that in Scotland the Palæozoic eruptions took place on the low ground and valleys, and continued to show themselves there during a long succession of volcanic periods. Especially noteworthy is the way in which the Permian vents were opened in lines and groups along the bottom of long narrow valleys in the Silurian uplands.[3]

Ordinary phase of an active Volcano.—The interval between two eruptions of an active volcano shows a gradual augmentation of energy. The crater, emptied by the last discharge, has its floor slowly upraised by the expansive force of the lava-column underneath. Vapours rise in constant outflow, accompanied sometimes by discharges of dust or stones. Through rents in the crater-floor red-hot lava may be seen only a few feet down. Where the lava is maintained at or above its fusion-point and possesses great liquidity, it may form boiling lakes, as in the great crater of Kilauea, where acres of seething lava may be watched throwing up fountains of molten rock, surging against the walls and re-fusing large masses that fall into the burning flood. The lava-column inside the pipe

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the Glacial Period. *Atti Lincei*, 3rd ser. vol. ii. (1878), p. 35. Stefani regards those of Tuscany as partly Miocene, partly Pliocene and post-Pliocene. (*Proc. Tosc. Soc. Nat. Pisa*, 1. p. xxi.)

[1] *Trans. Roy. Soc. Edin.* xxix. p. 437.

[2] "High Plateaux of Utah," *Geol. and Geog. Survey of Territories*, 1880, p. 62.

[3] *Quart. Journ. Geol. Soc.* vol. xlviii. (1892). Presidential Address, p. 156.

of a volcano is all this time gradually rising, until some weak part of the wall allows it to escape, or until the pressure of the accumulated vapours becomes great enough to burst through the hardened crust of the crater-floor and give rise to the phenomena of an eruption.

Conditions of Eruption.—Leaving for the present the general question of the cause of volcanic action, it may be here remarked that the conditions determining any particular eruption are still unknown. The explosions of a volcano may be to some extent regulated by the conditions of atmospheric pressure over the area at the time. In the case of a volcanic funnel like Stromboli, where, as Scrope pointed out, the expansive subterranean force within, and the repressive effect of atmospheric pressure without, just balance each other, any serious disturbance of that pressure might be expected to make itself evident by a change in the condition of the volcano. Accordingly, it has long been remarked by the fishermen of the Lipari Islands that in stormy weather there is at Stromboli a more copious discharge of steam and stones than in fine weather. They make use of the cone as a weather-glass, the increase of its activity indicating a falling, and the diminution a rising barometer. In like manner, Etna, according to Sartorius von Waltershausen, is most active in the winter months. Mr. Coan has indicated a relation between the eruptions of Kilauea and the rainy seasons of Hawaii, most of the discharges of that crater taking place within the four months from March to June.[1]

When we remember the connection, now indubitably established, between a more copious discharge of fire-damp in mines and a lowering of atmospheric pressure, we may be prepared to find a similar influence affecting the escape of vapours from the upper surface of the lava-column of a volcano; for it is not so much to the lava itself as to the expansive vapours impregnating it that the manifestations of volcanic activity are due. Among the Vesuvian eruptions since the middle of the seventeenth century, the number which took place in winter and spring has been to that of those which broke out in summer and autumn as 7 to 4. In Japan, also, the greater number of recorded eruptions have taken place during the cold months of the year, February to April.[2]

There may be other causes besides atmospheric pressure concerned in

[1] Dana, 'Characteristics of Volcanoes,' p. 125. For accounts of the volcanic phenomena of Hawaii, see W. Ellis, 'Polynesian Researches.' Wilkes' U.S. Exploring Expedition, 1838-42, "Geology," by J. D. Dana. The Rev. T. Coan, a missionary resident in Hawaii, observed the operations of the volcanoes for upwards of forty years, and published from time to time short notices of them in the *American Journal of Science*, vols. xiii. (1852) xiv. xv. xviii xxi. xxii. xxiii. xxv. xxvii. xxxvii. xl. xliii. xlvii. xlix. ; 3rd ser. ii. (1871) iv. vii viii. xiv. xviii. xx. xxi. xxii. (1881). Prof. Dana has recently revisited these volcanoes and fully discussed their phenomena in the *Amer. Journ. Sci.* vols. xxxiii.-xxxvii. (1887-89), and in his 'Characteristics of Volcanoes' See also C. E. Dutton, *Amer. Journ. Sci.* xxv. (1883), p. 219; *Report U.S. Geological Survey*, 1882-83. L. Green, 'Vestiges of the Molten Globe,' 1887. For an account of the remarkable glassy lavas of Hawaii, see E. Cohen, *Neues Jahrb.* 1880 (ii.), p. 23; and a general account of the petrography of the islands, by E. S. Dana, *Amer. Journ. Sci.* xxxvii. (1889), p. 441.

[2] J. Milne, *Seismol. Soc. Japan*, IX. Part ii. p. 174.

these differences; the preponderance of rain during the winter and spring may be one of these. According to Mr. Coan, previous to the great Hawaian eruption of 1868 there had been unusually wet weather, and to this fact he attributes the exceptional severity of the earthquakes and volcanic explosions. The greater frequency of Japanese volcanic eruptions and earthquakes in winter has been referred in explanation to the fact that the average barometric gradient across Japan is steeper in winter than in summer, while the piling up of snow in the northern regions gives rise to long-continued stresses, in consequence of which certain lines of weakness in the earth's crust are more prepared to give way during the winter months than they are in summer.[1] The effects of varying atmospheric pressure, however, can probably only slightly and locally modify volcanic activity. Eruptions, like the great one of Cotopaxi in 1877, have in innumerable instances taken place without, so far as can be ascertained, any reference to atmospheric conditions.

Kluge has sought to trace a connection between the years of maximum and minimum sun-spots and those of greatest and feeblest volcanic activity, and has constructed lists to show that years which have been specially characterised by terrestrial eruptions have coincided with those marked by few sun-spots and diminished magnetic disturbance.[2] Such a connection cannot be regarded as having yet been satisfactorily established. Again, the same author has called attention to the frequency and vigour of volcanic explosions at or near the time of the August meteoric shower. But in this case, likewise, the cited examples can hardly yet be looked upon as more than coincidences.

Periodicity of Eruptions.—At many volcanic vents the eruptive energy manifests itself with more or less regularity. At Stromboli, which is constantly in an active state, the explosions occur at intervals varying from three or four to ten minutes and upwards. A similar rhythmical movement has been often observed during the eruptions at other vents which are not constantly active. Volcano, for example, during its eruption of September 1873, displayed a succession of explosions which followed each other at intervals of from twenty to thirty minutes. At Etna and Vesuvius a similar rhythmical series of convulsive efforts has often been observed during the course of an eruption.[3] Among the volcanoes of the Andes a periodic discharge of steam has been observed; Mr. Whymper noticed outrushes of steam to proceed at intervals of from twenty to thirty minutes from the summit of Sangai, while during his inspection of the great crater of Cotopaxi, this volcano was seen to blow off steam at intervals of about half an hour.[4] At the eruption of the Japanese volcano, Oshima, in 1877, Mr. Milne observed that the explosions occurred nearly every two seconds, with occasional pauses of 15 or 20 seconds.[1] Kilauea, in Hawaii, seems to show a regular system of grand eruptive periods. Dana has pointed out that outbreaks of lava have taken place from that volcano at intervals of from eight to nine years, this being the time required to fill the crater up to the point of outbreak, or to a depth of 400 or 500 feet.[2]

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[1] J. Milne, *loc. cit.*

[2] 'Ueber Synchronismus und Antagonismus,' 8vo, Leipzig, 1863, p. 72. A. Poëy (*Comptes Rend.* lxxviii. (1874), p. 51) believes that among the 786 eruptions recorded by Kluge, between 1749 and 1861, the maxima correspond to periods of minimum in solar spots. See, however, *postea*, p. 281.

[3] G. Mercalli, *Atti. Soc. Ital. Sci. Nat.* xxiv. (1881).

[4] 'Travels among the Great Andes of the Equator,' 1892, pp. 74, 153.

Some volcanoes have exhibited a remarkable paroxysmal phase of activity, when after comparative or complete quiescence a sudden gigantic explosion has taken place, followed by renewed and prolonged repose. Vesuvius supplies the most familiar illustration of this character of volcanic energy. The great eruption of A.D. 79, which truncated the upper part of the old cone of Somma, was a true paroxysmal explosion, unlike anything that had preceded it within historic times, and far more violent than any subsequent manifestation of the same volcano. The crater-basin of Santorin, of which the islands Thera and Therasia represent portions of the rim, seems to have been blown out by some stupendous paroxysm in prehistoric times. The vast explosion of Krakatoa in 1883 was another memorable example. In these instances there was an earlier period of ordinary volcanic activity, during which a large cone was gradually built up. In the case of Somma and Krakatoa the energy died down for a time, and the paroxysm came with hardly any premonitory warning. It has been succeeded by a time of comparatively feeble activity. At Vesuvius the great explosion of 1631, which terminated nearly 1500 years of quiescence, may be regarded as a minor paroxysm, since which the mountain has remained more continuously active.

General sequence of events in an Eruption.—The approach of an eruption is not always indicated by any premonitory symptoms, for many tremendous explosions are recorded to have taken place in different parts of the world without perceptible warning. Much in this respect would appear to depend upon the condition of liquidity of the lava, and the amount of resistance offered by it to the passage of the escaping vapours through its mass. In Hawaii, where the lavas are remarkably liquid, vast outpourings of them have taken place quietly without earthquakes during the present century. But even there, the great eruption of 1868 was accompanied by violent earthquakes.

The eruptions of Vesuvius are often preceded by failure or diminution of wells and springs. But more frequent indications of an approaching outburst are conveyed by sympathetic movements of the ground. Subterranean rumblings and groanings are heard; slight tremors succeed, increasing in frequency and violence till they become distinct earthquake shocks. The vapours from the crater grow more abundant, as the lava-column in the pipe or funnel of the volcano ascends, forced upward and kept in perpetual agitation by the passage of elastic vapours through its mass. After a long previous interval of quiescence, there may be much solidified lava towards the top of the funnel, which will restrain the ascent of the still molten portion underneath. A vast pressure is thus exercised on the sides of the cone, which, if too weak to resist, will open in one or more rents, and the liquid lava will issue from the outer slope of the mountain; or the energies of the volcano will be directed towards clearing the obstruction in the chief throat, until with tremendous explosions, and the rise of a vast cloud of dust and fragments, the bottom and sides of the crater are finally blown out, and the top of the cone disappears. The lava may now escape from the lowest part of the lip of the crater, while, at the same time, immense numbers of red-hot bombs, scoriæ, and stones are shot up into the air. The lava at first rushes down like one or more rivers of melted iron, but, as it cools, its rate of motion lessens. Clouds of steam rise from its surface, as well as from the central crater. Indeed, every successive paroxysmal convulsion of the mountain is marked, even at a distance, by the rise of huge ball-like wreaths or clouds of steam, mixed with dust and stones, forming a column which towers sometimes a couple of miles or more above the summit of the cone. By degrees these eructations diminish in frequency and intensity. The lava ceases to issue, the showers of stones and dust decrease, and after a time, which may vary from hours to days or months, even in the *régime* of the same mountain, the volcano becomes once more tranquil.[1]

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[1] *Trans. Seism. Soc. Japan*, ix. part ii. p. 82.

[2] 'Characteristics of Volcanoes.' p. 124. On periodicity of eruptions, see Kluge, *Neues Jahrb.* 1862, p. 582.

In the investigation of the subject, the student will naturally devote attention specially to those aspects of volcanic action which have more particular geological interest from the permanent changes with which they are connected, or from the way in which they enable us to detect and realise conditions of volcanic energy in former periods.

Fissures.—The convulsions which culminate in the formation of a volcano usually split open the terrestrial crust by a more or less nearly rectilinear fissure, or by a system of fissures. In the subsequent progress of the mountain, the ground at and around the focus of action is liable to be again and again rent open by other fissures. These tend to diverge from the focus; but around the vent where the rocks have been most exposed to concussion, the fissures sometimes intersect each other in all directions. In the great eruption of Etna, in the year 1669, a series of six parallel fissures opened on the side of the mountain. One of these, with a width of two yards, ran for a distance of 12 miles, in a somewhat winding course, to within a mile of the top of the cone.[2] Similar fissures, but on a smaller scale, have often been observed on Vesuvius and other volcanoes.[3] A fissure sometimes reopens for a subsequent eruption.

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[1] See Schmidt's narrative of the eruption of Vesuvius in May 1855 (*ante*, p. 195). An account of the great eruption of Cotopaxi in June 1877, by Dr. Th. Wolf, will be found in *Neues Jahrb.* 1878, p. 113.

[2] For fissures on Etna, see Silvestri, *Boll. R. Geol. Com. Ital.* 1874.

[3] For a description of those of Iceland (which run chiefly N.E. to S.W., and N. to S.) see T. Kjerulf, *Nyt. Mag.* xxi. 147.

Two obvious causes may be assigned for the pushing upward of a crater-floor and the fissuring of a volcanic cone:—(1) the enormous pressure of the dissolved vapours or gases acting upon the walls and roof of the funnel and convulsing the cone by successive explosions; and (2) the hydrostatic pressure of the lava-column in the funnel, which may be taken to be about 120 lbs. per square inch, or nearly 8 tons on the square foot, for each 100 feet of depth. Both of these causes may act simultaneously, and their united effect has been to uplift enormous superincumbent masses of solid rock and to produce a wide-spread series of long and continuous fissures reaching from unknown depths to various distances from the surface and even opening up sometimes on the surface. These results of the expansive energy of volcanic action are of special interest to the geologist, for he encounters evidence of similar operations in former times preserved in the crust of the earth (see Book IV. Part VII. Sect. i.)

Into rents thus formed, the water-substance or vapour rises with great expansive force, followed by the lava which solidifies there like iron in a mould. Where fissures are vertical or highly inclined the igneous rock takes the form of *dykes* or *veins*; where the intruded material has forced its way more or less in a horizontal direction between strata of tuff, beds of non-volcanic sediments, or flows of lava, it takes the form of *sheets* (*sills*) or *beds*. The cliffs of many an old crater show how marvellously they have been injected by such veins, dykes, or sheets of lava. Those of Somma, and the Valle del Bove on Etna (Fig. 42), which have long been known, project now from the softer tuffs like walls of masonry.[1] The

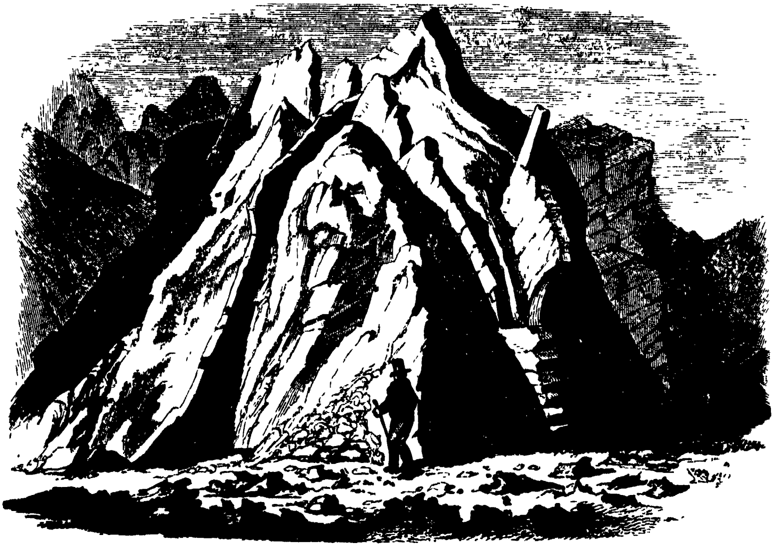

Fig. 42.—View of Lava-dykes, Valle del Bove, Etna (Abich).

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[1] S. von Waltershausen, 'Der Aetna,' ii. p. 341.

crater cliffs of Santorin also present an abundant series of dykes. The permanent separation of the walls of fissures by the consolidation of the lava that rises in them as dykes must widen the dimensions of a cone, for the fissures are not due to shrinkage, although doubtless the loosely piled fragmentary materials, in the course of their consolidation, develop lines of joint. Sometimes the lava has evidently risen in a state of extreme fluidity, and has at once filled the rents prepared for it, cooling rapidly on the outside as a true volcanic glass, but assuming a distinctly crystalline structure inside (*ante*, p. 171). Dykes of this kind, with a vitreous crust on their sides, may be seen on the crater-wall of Somma, and not uncommonly among basalt dykes in Iceland and Scotland. In other cases, the lava had probably already acquired a more viscous or even lithoid character ere it rose in the fissure, and in this condition was able to push aside and even contort the strata of tuff through which it made its way (Fig. 43). There can be little doubt that in the architecture of a volcano, dykes must act the part of huge beams and girders (Fig. 44), binding the loose tuffs and intercalated lavas together, and strengthening the cone against the effects of subsequent convulsions.

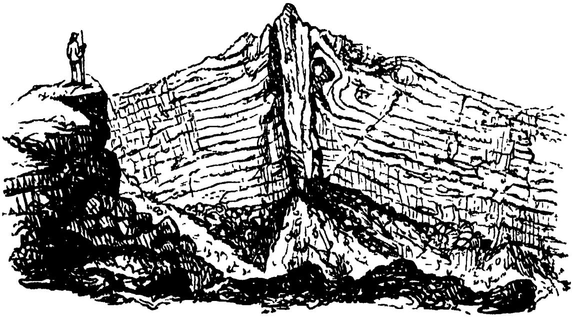

Fig. 43.—Dyke contorting beds of tuff. Crater of Vesuvius (Abich).

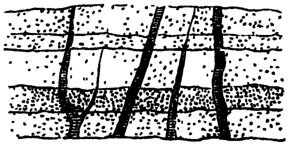

Fig. 44.—Section of Dykes of Lava traversing the bedded tuffs of a volcanic cone.

From this point of view, an explanation suggests itself of the observed alternations in the character of a volcano's eruptions. These alternations may depend in great measure upon the relation between the height of the cone, on the one hand, and the strength of its sides, on the other. When the sides have been well braced together by interlacing dykes, and further thickened by the spread of volcanic materials all over their slopes, they may resist the effects of explosion and of the pressure of the ascending lava-column. In this case, the volcano may find relief only from its summit, and if the lava flows forth, it will do so from the top of the cone. As the cone increases in elevation, however, the pressure from within upon its sides augments. Eventually egress is once more established on the flanks by means of fissures, and a new series of lava-streams is poured out over the lower slopes (*postea*, p. 248).

In the deeper portions of a volcanic vent the convulsive efforts of the lava-column to force its way upward must often produce lateral as well as vertical rifts, and into these the molten material will rush, exerting as it goes an enormous upward pressure on the mass of rock overlying it. At a modern volcano these subterranean manifestations cannot be seen, but among the volcanoes of Tertiary and older time they have been revealed by the progress of denudation. Some of these older examples teach us the prodigious upheaving power of the sheets of molten rock intruded between volcanic or other strata. An account of this structure (sills, laccolites), with reference to some examples of it, will be found in Book IV. Part VII.[1]

Though lava very commonly issues from the lateral fissures on a volcanic cone, it may sometimes approach the surface in them without actually flowing out. The great fissure on Etna in 1669, for example, was visible even from a distance, by the long line of vivid light which rose from the incandescent lava within. Again, it frequently happens that minor volcanic cones are thrown up on the line of a fissure, either from the congelation of the lava round the point of emission, or from the accumulation of ejected scoriæ round the fissure-vent. One of the most remarkable examples of this kind is that of the Laki fissure in Iceland, the whole length of which (12 miles) bristles with small cones and craters almost touching each other.[2]

Explosions.—Apart from the appearance of visible fissures, volcanic energy may be, as it were, concentrated on a given point, which will usually be the weakest in the structure of that part of the terrestrial crust, and from which the solid rock, shattered into pieces, is hurled into the air by the enormous expansive energy of the volcanic vapours.[3] This operation has often been observed in volcanoes already formed, and has even been witnessed on ground previously unoccupied by a volcanic vent. The history of the cone of Vesuvius brings before us a long series of such explosions, beginning with that of A.D. 79, and coming down to the present day (Fig. 45). Even now, in spite of all the lava and ashes poured out during the last eighteen centuries, it is easy to see how stupendous must have been that earliest explosion, by which the southern half of the ancient crater was blown out. At every successive important eruption, a similar but minor operation takes place within the present cone. The hardened cake of lava forming the floor is burst open, and with it there usually disappears much of the upper part of the cone, and sometimes, as in 1872, a large segment of the crater-wall. The Valle del Bove on the eastern flank of Etna is a chasm probably due mainly to some gigantic prehistoric explosion.[4] The islands of Santorin (Figs. 65 and 66) bring before us evidence of a prehistoric catastrophe of a similar nature, by which a large volcanic cone was blown up. The existing outer islands are a chain of fragments of the periphery of the cone, the centre of which is now occupied by the sea. In the year 1538 a new volcano, Monte Nuovo, was formed in 24 hours on the margin of the Bay of Naples. An opening was drilled by successive explosions, and such quantities of stones, scoriæ, and ashes were thrown out from it as to form a hill that rose 440 English feet above the sea-level, and was more than a mile and a half in circumference. Most of the fragments now to be seen on the slopes of this cone and inside its beautifully perfect crater are of various volcanic rocks, many of them being black scoriæ; but pieces of Roman pottery, together with fragments of the older underlying tuff, and some marine shells, have been obtained—doubtless part of the soil and subsoil dislocated and ejected during the explosions.

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[1] See particularly the description of intrusive sheets or laccolites.

[2] A. Helland, 'Lakis Kratere og Lava-strome,' cited on p. 202. On this straight fissure some 500 craters rise, varying from 5 to 450 feet high.

[3] See Daubrée's experiments on the mechanical effects of gas at high pressures, *Comptes Rend.* cxi. cxii. cxiii., and *Bull. Soc. Geol. France*, xix. (1891), p. 313.

[4] 'Der Aetna,' p. 400.

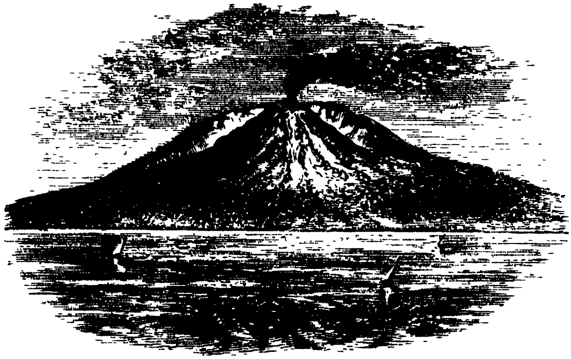

Fig. 45.—View of Vesuvius from the south,
Showing the remaining part of the old crater-wall of Somma behind.

One of the most stupendous volcanic explosions on record was that of Krakatoa in the Sunda Strait on the 26th and 27th of August 1883.[1] After a series of convulsions, the greater portion of the island was blown out with a succession of terrific detonations which were heard more than 150 miles away. A mass of matter, estimated at about $1\frac{1}{8}$ cubic mile in bulk, was hurled into the air in the form of lapilli, ashes, and the finest volcanic dust. The effects of this volcanic outburst were marked both upon the atmosphere and the ocean. A series of barometrical disturbances passed round the globe in opposite directions from the volcano at the rate of about 700 miles an hour. The air-wave, travelling from east to west is supposed to have passed three and a quarter times round the earth (or 82,200 miles) before it ceased to be perceptible.[2] The sea in the neighbourhood was thrown into waves, one of which was computed to have risen more than 100 feet above tide-level, destroying towns, villages, and 36,380 people. Oscillations of the water were perceptible even at Aden,

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[1] See 'The Eruption of Krakatoa,' by a Committee of the Royal Society, 1888. 'Krakatau,' R. D. M. Verbeck, Batavia, 1886.

[2] Scott and Strachey, *Proc. Roy. Soc.* xxxvi. (1883). Royal Society's Report, p. 57.

1000 miles distant, at Port Elizabeth in South Africa, 5450 miles, and among the islands of the Pacific Ocean, and they are computed to have travelled with a maximum velocity of 467 statute miles in the hour.[1]

It is not necessary, and it does not always happen, that any actual solid or liquid volcanic rock is erupted by explosions that shatter the rocks through which the funnel passes. Thus, among the cones of the extinct volcanic tract of the Eifel, some occur which consist entirely, or nearly so, of comminuted débris of the surrounding Devonian greywacke and slate through which the various volcanic vents have been opened (see pp. 200, 244, 585). Evidently, in such cases, only elastic vapours forced their way to the surface; and we see what probably often takes place in the early stages of a volcano's history, though the fragments of the underlying disrupted rocks are in most instances buried and lost under the far more abundant subsequent volcanic materials. Sections of small ancient volcanic "necks" or pipes sometimes afford an excellent opportunity of observing that these orifices were originally opened by the blowing out of the solid crust and not by the formation of fissures. Examples will be cited in later pages from Scottish volcanic areas of Old Red Sandstone, Carboniferous, and Permian age. The orifices are there filled with fragmentary materials, wherein portions of the surrounding and underlying rocks form a noticeable proportion.[2] (See pp. 584-589).

Showers of Dust and Stones.—A communication having been opened, either by fissuring or explosion, between the heated interior and the surface, fragmentary materials are commonly ejected from it, consisting at first mainly of the rocks through which the orifice has been opened, afterwards of volcanic substances. In a great eruption, vast numbers of red-hot stones are shot up into the air, and fall back partly into the crater and partly on the outer slopes of the cone. According to Sir W. Hamilton, cinders were thrown by Vesuvius, during the eruption of 1779, to a height of 10,000 feet. Instances are known where large stones, ejected obliquely, have described huge parabolic curves in the air, and fallen at a great distance. Stones 8 lbs. in weight occur among the ashes which buried Pompeii. The volcano of Antuco in Chili is said to send stones flying to a distance of 36 (?) miles, Cotopaxi is reported to have hurled a 200-ton block 9 miles,[3] and the Japanese volcano, Asama, is said to have ejected many blocks of stone, measuring from 40 to more than 100 feet in diameter.[4]

But in many great eruptions, besides a constant shower of stones and scoriæ, a vast column of exceedingly fine dust rises out of the crater, sometimes to a height of several miles, and then spreads outwards like a sheet of cloud. The remarkable fineness of this dust may be understood from the fact that during great volcanic explosions no boxes, watches, or close-fitting joints have been found to be able to exclude it. Mr. Whymper collected some dust that fell 65 miles away from Cotopaxi, and which was so fine that from 4000 to 25,000 particles were required to weigh a grain.[1] So dense is the dust-cloud as to obscure the sun, and for days together the darkness of night may reign for miles around the volcano. In 1822, at Vesuvius, the ashes not only fell thickly on the villages round the base of the mountain, but travelled as far as Ascoli, which is 56 Italian miles distant from the volcano on one side, and as Casano, 105 miles on the other. The eruption of Cotopaxi, on 26th June 1877, began by an explosion that sent up a column of fine ashes to a prodigious height into the air, where it rapidly spread out and formed so dense a canopy as to throw the region below it into total darkness.[2] So quickly did it diffuse itself, that in an hour and a half, a previously bright morning became at Quito, 33 miles distant, a dim twilight, which in the afternoon passed into such darkness that the hand placed before the eye could not be seen. At Guayaquil, on the coast, 150 miles distant, the shower of ashes continued till the 1st of July. Dr. Wolf collected the ashes daily, and estimated that at that place there fell 315 kilogrammes on every square kilometre during the first thirty hours, and on the 30th of June, 209 kilogrammes in twelve hours.[3] During a much less important eruption of the same mountain on 3rd July 1880, the amount of volcanic dust ejected, according to Mr. Whymper, could not have been less, and was probably vastly more, than two millions of tons,[4] equivalent to a mass of lava containing more than 150,000 cubic feet.

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[1] Wharton, Royal Society's Report, p. 89. For a great Japanese explosion, see *Nature*, 13th Sept. 1888.

[2] *Trans. Roy. Soc. Edin.* xxix. p. 458; *Quart. Journ. Geol. Soc.* (1892), President's Address, pp. 86, 118, 135, 143, 153.

[3] D. Forbes, *Geol. Mag.* vii. p. 320.

[4] J. Milne, *Seism. Soc. Japan,* ix. p. 179, where an excellent account of the volcanoes of Japan is given. See also 'The Volcanoes of Japan' by J. Milne and W. K. Burton.

The explosion of Krakatoa in August 1883 was accompanied by the discharge of enormous quantities of volcanic dust, some of which was carried to vast distances. It was estimated that the clouds of fine dust were hurled from that volcano to a height of 17 miles, and the darkness which they caused extended for 150 miles from the focus of eruption. The diffusion and continued suspension of the finer particles of this dust in the upper air has been regarded as the probable cause of the remarkably brilliant sunsets of the following winter and spring over a large part of the earth's surface.[5] One of the most stupendous outpourings of volcanic ashes on record took place, after a quiescence of 26 years, from the volcano Coseguina, in Nicaragua, during the early part of the year 1835. On that occasion, utter darkness prevailed over a circle of 35 miles radius, the ashes falling so thickly that, even 8 leagues from the mountain, they covered the ground to a depth of about 10 feet. It was estimated that the rain of dust and sand fell over an area at least 270 geographical miles in diameter. Some of the finer materials, thrown so high as to come within the influence of an upper air-current, were borne away eastward, and fell, four days afterwards, at Kingston, in Jamaica—a distance of 700 miles. During the great eruption of Sumbawa, in 1815, the dust and stones fell over an area of nearly one million square miles, and were estimated by Zollinger to amount to fully fifty cubic miles of material, and by Junghuhn to be equal to one hundred and eighty-five mountains like Vesuvius. Towards the end of last century, during a time of great disturbance among the Japanese volcanoes, one of them, Sakurajima, threw out so much pumiceous material that it was possible to walk a distance of 23 miles upon the floating débris in the sea.

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[1] Royal Society Report on Krakatoa, p. 183.

[2] During the comparatively insignificant eruption of this volcano in 1880 Mr. Whymper noticed that a column of inky blackness, formed doubtless of volcanic dust, went straight up into the air with such velocity that in less than a minute it had risen 20,000 feet above the rim of the crater, or 40,000 feet above the sea. 'Travels amongst the Great Andes,' p. 322.

[3] *Neues Jahrb.* 1878, p. 141. An account of this eruption is given by Mr. Whymper in his 'Travels amongst the Great Andes,' chap. vi.

[4] 'Travels amongst the Great Andes,' p. 328.

[5] Royal Society Report, pp. 151-463.

An inquiry into the origin of these showers of fragmentary materials brings vividly before us some of the essential features of volcanic action. We find that bombs, slags, and lapilli may be thrown up in comparatively tranquil states of a volcano, but that the showers of fine dust are discharged with violence, and only appear when the volcano becomes more energetic. Thus, at the constantly, but quietly, active volcano of Stromboli, the column of lava in the pipe may be watched rising and falling with a slow rhythmical movement. At every rise, the surface of the lava swells up into blisters several feet in diameter, which by and by burst with a sharp explosion that makes the walls of the crater vibrate. A cloud of steam rushes out, carrying with it hundreds of fragments of the glowing lava, sometimes to a height of 1200 feet. It is by the ascent of steam through its mass, that a column of lava is kept boiling at the bottom of the crater, and by the explosion of successive larger bubbles of steam, that the various bombs, slags, and fragments of lava are torn off and tossed into the air. It has often been noticed at Vesuvius that each great concussion is accompanied by a huge ball-like cloud of steam which rushes up from the crater. Doubtless it is the sudden escape of that steam which causes the explosion.

The varying degree of liquidity or viscosity of the lava probably modifies the force of explosions, owing to the different amounts of resistance offered to the upward passage of the absorbed gases and vapours. Thus explosions and accompanying scoriæ are abundant at Vesuvius, where the lavas are comparatively viscid; they are almost unknown at Kilauea, where the lava is remarkably liquid.

In tranquil conditions of a volcano, the steam, whether collecting into larger or smaller vesicles, works its way upward through the substance of the molten lava, and as the elasticity of this compressed vapour overcomes the pressure of the overlying lava, it escapes at the surface, and there the lava is thus kept in ebullition. But this comparatively quiet operation, which may be watched within the craters of many active volcanoes, does not produce clouds of fine dust. The collision or friction of millions of stones ascending and descending in the dark column above the crater must doubtless cause much dust and sand. But the explosive action of steam is probably also an immediate cause of much trituration. The aqueous vapour or water-gas which is so largely dissolved in many lavas must exist within the lava-column, under an enormous pressure, at a temperature far above its critical point (p. 194), even at a white heat, and therefore possibly in a state of dissociation. The sudden ascent of lava so constituted relieves the pressure rapidly without sensibly affecting the temperature of the mass. Consequently, the white-hot gases or vapours at length explode, and reduce the molten mass to the finest powder, like water shot out of a gun.[1]

Evidently no part of the operations of a volcano has greater geological significance than the ejection of such enormous quantities of fragmentary matter. In the first place, the fall of these loose materials round the orifice of discharge is one main cause of the growth of the volcanic cone. The heavier fragments gather around the vent, and there too the thickest accumulation of dust and sand takes place. Hence, though successive explosions may blow out the upper part of the crater-walls and prevent the mountain from growing so rapidly in height, every eruption must increase the diameter of the cone. In the second place, as every shower of dust and sand adds to the height of the ground on which it falls, thick volcanic accumulations may be formed far beyond the base of the mountain. The volcano of Sangay, in Ecuador, for instance, has buried the country around it to a depth of 4000 feet under its ashes.[2] In such loose deposits are entombed trees and other kinds of vegetation, together with the bodies of animals, as well as the works of man. In some cases, where the layer of volcanic dust is thin, it may merely add to the height of the soil, without sensibly interfering with the vegetation. But it has been observed at Santorin that though this is true in dry weather, the fall of rain with the dust at once acts detrimentally. On the 3rd of June 1866, the vines were there withered up, as if they had been burnt, along the track of the smoke cloud.[3] By the gradual accumulation of volcanic ashes, new geological formations arise which, in their component materials, not only bear witness to the volcanic eruptions that produced them, but preserve a record of the land-surfaces over which they spread. In the third place, besides the distance to which the fragments may be hurled by volcanic explosions, or to which they may be diffused by the ordinary aerial movements, we have to take into account the vast spaces across which the finer dust is sometimes borne by upper air-currents. In the instance already cited, ashes from Coseguina fell 700 miles away, having been carried all that long distance by a high counter-current of air, moving apparently at the rate of about seven miles an hour in an opposite direction to that of the wind which blew at the surface. By the Sumbawa eruption, also referred to above, the sea west of Sumatra was covered with a layer of ashes two feet thick. On several occasions ashes from the Icelandic volcanoes have fallen so thickly between the Orkney and Shetland Islands, that vessels passing there have had the unwonted deposit shovelled off their decks in the morning. In the year 1783, during the memorable eruption of Skaptar-Jökull, so vast an amount of fine dust was ejected that the atmosphere over Iceland continued loaded with it for months afterwards. It fell in such quantities over parts of Caithness —a distance of 600 miles—as to destroy the crops; that year is still spoken of by the inhabitants as the year of "the ashie." Traces of the same deposit have been observed in Norway, and even as far as Holland.[1] Hence it is evident that volcanic accumulations may take place in regions many hundreds of miles distant from any active volcano. A single thin layer of volcanic detritus in a group of sedimentary strata would not thus of itself prove the existence of contemporaneous volcanic action in its neighbourhood. Failing other proof of adjacent volcanic activity, it might have been wind-borne from a volcano in a distant region.

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[1] Messrs. Murray and Renard (*Proc. Roy. Soc. Edin.* xii. (1884), p. 480) concluded that the fragmentary condition and the fresh fractures of the dust-particles of the Krakatoa eruption were due to a tension phenomenon, which affects these vitreous matters in a manner analogous to what is observed in "Rupert's drops."

[2] D. Forbes, *Geol. Mag.* vii. 320.

[3] Fouqué, 'Santorin,' p. 81.

Lava-streams.—At its exit from the side of a volcano, lava glows with a white heat, and flows with a motion which has been compared to that of honey or of melted iron. It soon becomes red, and like a coal fallen from a hot fireplace, rapidly grows dull as it moves along, until it assumes a black, cindery aspect. At the same time the surface congeals, and soon becomes solid enough to support a heavy block of stone. The aspect of the stream varies with the composition and fluidity of the lava, form of the ground, angle of slope, and rapidity of flow. Viscous lavas, like those of Vesuvius, break up along the surface into rough brown or black cinder-like slags and irregular ragged cakes, bristling with jagged points ("*aa*" [2]), which, in their onward motion, grind and grate against each other with a harsh metallic sound, sometimes rising into rugged mounds or becoming seamed with rents and gashes, at the bottom of which the red-hot glowing lava may be seen (Fig. 46). In lavas possessing somewhat greater fluidity, the surface presents froth-like, curving lines, as in the scum of a slowly flowing river, or is arranged in curious ropy folds, as the layers have successively flowed over each other and congealed ("*pahoehoe*" [2]). These, and many other fantastic coiled shapes were exhibited by the Vesuvian lava of 1858, and are admirably displayed by the peculiarly liquid glassy lavas of Kilauea.[2] Basalts possessing extreme liquidity have flowed for great distances with singularly smooth surfaces. A large area which has been flooded with lava is perhaps the most hideous and appalling scene of desolation anywhere to be found on the surface of the globe.

A lava-stream usually spreads out as it descends from its point of escape, and moves more slowly. Its sides look like huge embankments, or like some of the long mounds of "clinkers" in a great manufacturing district. The advancing end is often much steeper, creeping onward like a great wall or rampart, down the face of which the rough blocks of hardened lava are ever rattling (Fig. 47).

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[1] Nordenskiöld, *Geol. Mag.* 2nd dec. iii. p. 292. G. vom Rath, *Monatsber. K. Preuss. Akad. Wiss.* 1876, p. 282. *Neues Jahrb.* 1876, p. 52, and *postea*, p. 338.

[2] For descriptions of Vesuvian lava-streams, see the various memoirs and works cited, *ante*, p. 195. For those of Etna, Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna,' ii. p. 390. The rugged scoriaceous lava-surfaces are known in Hawaii as *aa*, the smooth coiled and ropy surfaces are there called *pahoehoe*. Dana, 'Characteristics of Volcanoes,' p. 9. The same stream of lava may exhibit both these aspects in different parts of its course. *Ibid.* p. 209 and Mr. Johnston-Lavis' papers on Vesuvius, already cited p. 195.

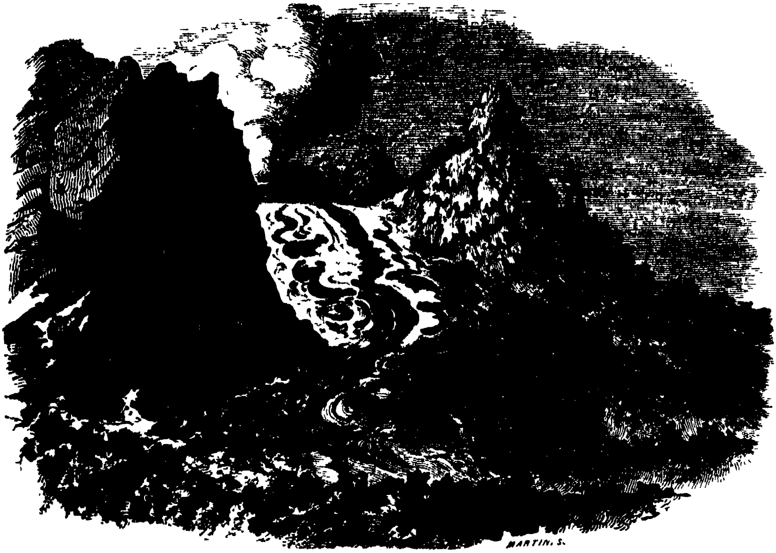

Fig. 46.—View of portion of a Lava-stream on Vesuvius (Abich).

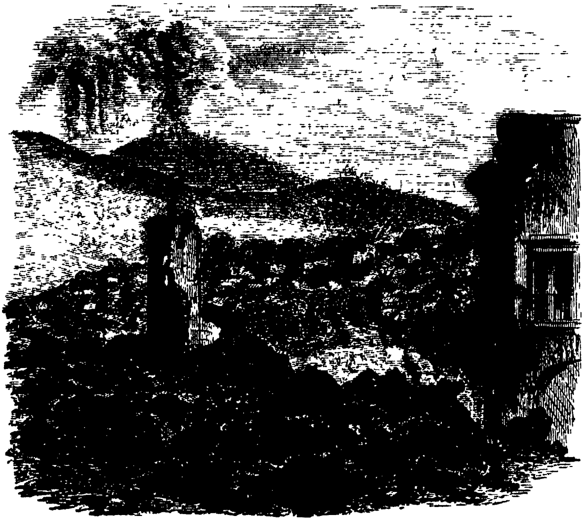

Fig. 47.—View of houses surrounded and partly demolished by the Lava of Vesuvius, 1872.

Outflow of Lava.—This appears to be immediately due to the expansion of the absorbed vapours and gases in the molten rock. Though these vapours may reach the surface, and even produce tremendous explosions, without an actual outcome of lava, yet so intimately are vapours and lava commingled in the subterranean reservoirs, that they commonly rise together, and the explosions of the one lead to the outflow of the other. The first point at which the lava makes its appearance at the surface will largely depend upon the structure of the ground. Two causes have been assigned on a foregoing page (p. 209) for the fissuring of a volcanic cone. As the molten mass rises within the chimney of the volcano, continued explosions of vapour take place from its upper surface. The violence of these may be inferred from the vast clouds of steam, ashes, and stones hurled to so great a height into the air, and from the concussions of the ground, which may be felt at distances of more than 100 miles from the volcano. It need not be a matter of surprise, therefore, that the sides of a great vent, exposed to shocks of such intensity, should at last give way, and that large divergent fissures should be opened down the cone. Again, the hydrostatic pressure of the column of lava must, at a depth of 1000 feet below the top of the column, exert a pressure of between 70 and 80 tons on each square foot of the surrounding walls (p. 209). We may well believe that such a force, acting upon the walls of a funnel already shattered by a succession of terrific explosions, may prove too great for their resistance. When this happens, the lava pours forth from the outside of the cone. On a much-fissured cone, lava may issue freely from many points, so that a volcano so affected has been graphically described as "sweating fire."

In a lofty volcano, lava occasionally rises to the lip of the crater and flows out there; but more frequently it escapes from some fissure or orifice in a weak part of the cone. In minor volcanoes, on the other hand, where the explosions are less violent, and where the thickness of the cone in proportion to the diameter of the funnel is often greater, the lava very commonly rises into the crater. Should the crater-walls be too weak to resist the pressure of the molten mass, they give way, and the lava rushes out from the breach. This is seen to have happened in several of the puys of Auvergne, so well figured and described by Scrope (Fig. 48).[1] But if the crater be massive enough to withstand the pressure, the lava may at last flow out from the lowest part of the rim.

In a tall column of molten lava, there may be a variation in the density of its different parts, the heaviest naturally gravitating to the bottom. It has been observed by Ch. Vélain that at the Isle of Bourbon (Réunion), the lavas escaping from the base of the volcanic cone are denser and more basic than those which flow out from the lip of the crater.[2]

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[1] For descriptions of this region, see Scrope's 'Geology and Extinct Volcanoes of Central France,' 2d edit. 1858. H. Lecoq's 'Epoques géologiques de l'Auvergne,' 1867. Michel Lévy, *Bull. Soc. Géol. France*, xviii. (1890), p. 688. The succession of volcanic rocks in Velay is described by M. Boule, *Bull. Soc. Géol. France*, xviii. (1889), p. 174, and in *Bull. Carte Géol. de la France*, No. 28 (1892); see also *op. cit.* No. 13 for a memoir by P. Termier.

[2] 'Les Volcans,' p. 36. For references relating to this island, see p. 243.

As soon as the molten rock reaches the surface, the superheated water-vapour or gas, dissolved within its mass, escapes copiously, and hangs as a dense white cloud over the moving current. The lava-streams of Vesuvius sometimes appear with as dense a steam-cloud at their lower ends as that which escapes at the same time from the main crater. Even after the molten mass has flowed several miles, steam continues to rise abundantly both from its end and from numerous points along its surface, and continues to do so for many weeks, months, or it may be for several years.

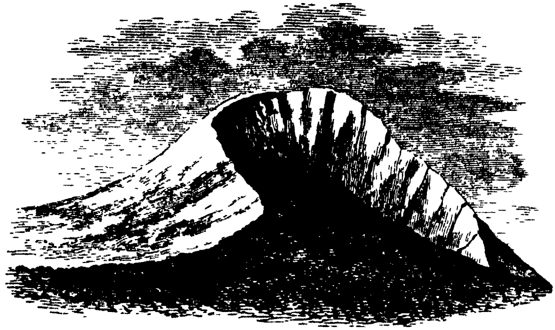

Fig. 48.—View of one of the Tuff-cones of Auvergne, broken down on one side by the escape of a stream of Lava. (After Scrope.)

Should the point of escape of a lava-stream lie well down on the cone, far below the summit of the lava-column in the funnel, the molten rock, on its first escape, driven by hydrostatic pressure, will sometimes spout up high into the air—a fountain of molten rock. This was observed in 1794 on Vesuvius, and in 1832 on Etna. In the eruption of 1852 at Mauna Loa, an unbroken fountain of lava, from 200 to 700 feet in height and 1000 feet broad, burst out at the base of the cone. Similar "geysers" of molten rock have subsequently been noticed in the same region. Thus in March and April 1868, four fiery fountains, throwing lava to heights varying from 500 to 1000 feet, continued to play for several weeks. According to Mr. Coan, such outbursts take place from the bottom of a column of lava 3000 feet high. The volcano of Mauna Loa strikingly illustrates another feature of volcanic dynamics in the position and outflow of lava. It bears upon its flanks at a distance of 20 miles, but 10,000 feet lower, the huge crater Kilauea. As Dana has pointed out, these orifices form part of one mountain, yet the column of lava stands 10,000 feet higher in one conduit than in the other. On a far smaller scale the same independence occurs among the several pipes of some of the geysers in the Yellowstone region of North America.

From the wide extent of basalt-dykes, such as those of Tertiary age in Britain, which rise to the surface at a distance of 200 miles from the main remnants of the volcanic outbursts of their time, and are found over an area of perhaps 100,000 square miles, it is evident that molten lava may sometimes occupy a far greater space within the crust than might be inferred from the dimensions and outpourings even of the largest volcanic cone. There can be no doubt that vast reservoirs of melted rock, impregnated with superheated vapours, must formerly have existed, if they do not exist still, beneath extensive tracts of country (p. 583). Yet even in these more stupendous manifestations of volcanism, the lava should be regarded rather as the sign than as the cause of volcanic action. The cause of the ascent of the lava in volcanic pipes is still obscure: it may possibly be due to the compression arising from the secular contraction of the earth. But it is doubtless the pressure of the imprisoned vapour, and its struggles to get free, which produce the subterranean earthquakes and the explosions from the vents. As soon as the vapour finds relief, the terrestrial commotion calms down again, until another accumulation of vapour demands a repetition of the same phenomena.

Rate of flow of Lava.—The rate of movement is regulated by the fluidity of the lava, by its volume, and by the form and inclination of the ground. Hence, as a rule, a lava-stream moves faster at first than afterwards, because it has not had time to stiffen, and its slope of descent is usually steeper than farther down the mountain. One of the most fluid and swiftly flowing lava-streams ever observed on Vesuvius was that erupted on 12th August 1805. It is said to have rushed down a space of 3 Italian ($3\frac{2}{3}$ English) miles *in the first four minutes*, but to have widened out and moved more slowly as it descended, yet finally to have reached Torre del Greco in three hours. A lava erupted by Mauna Loa in 1852 went as fast as an ordinary stage-coach, or fifteen miles in two hours; but some of the lavas from that mountain have in parts of their course moved with double that rapidity. Long after a current has been deeply crusted over with slags and rough slabs of lava, it may continue to creep slowly forward for weeks or even months.

It happens sometimes that, as the lava moves along, the still molten mass inside bursts through the outer hardened and deeply seamed crust, and rushes out with, at first, a motion much more rapid than that of the main stream. Any sudden change in the form or slope of the ground affects the flow of the lava. Thus, reaching the edge of a steep defile or cliff, the molten rock pours over in a cataract of glowing, molten rock, with clouds of steam, showers of fragments, and a noise utterly indescribable. Or, on the other hand, encountering a ridge or hill across its path, it accumulates until it either finds egress round the side or actually overrides and entombs the obstacle. The hardened crust or shell, within which the still fluid lava moves, serves to keep the mass from spreading. Here and there, inside this crust, the lava subsides, leaving cavernous spaces and tunnels into which, when the whole is cold, one may creep, and which are sometimes festooned with stalactites of lava (p. 227).

Size of Lava-streams.—In some cases, lava escaping from craters or fissures comes to rest before reaching the base of the slopes, like the obsidian current which has congealed on the side of the little volcanic island of Volcano.[1] In other instances, the molten rock not only reaches the plains but flows for many miles away from the point of eruption. Sartorius von Waltershausen computed the lava emitted by Etna in 1865 at 92 millions of cubic metres, that of 1852 at 420 millions, that of 1669 at 980 millions, and that of a pre-historic lava-stream near Randazzo at more than 1000 millions.[1] The most stupendous outpouring of lava on record was that which took place in Iceland in the year 1783. Successive streams issued from a fissure about 12 miles long, filling up river-gorges which were sometimes 600 feet deep and 200 feet broad, and advancing into the alluvial plains in lakes of molten rock 12 to 15 miles wide and 100 feet deep. Two currents of lava which, filling up the valley of the Skapta, escaped in nearly opposite directions, extended for 45 and 50 miles respectively, their usual thickness being 100 feet. Bischof estimated that the total amount of lava poured forth during this single eruption "surpassed in magnitude the bulk of Mont Blanc."[2]

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[1] Recent eruptions in this island have consisted entirely of ashes. A. Baltzer, *Zeitsch.*

Varying liquidity of Lava.—All lava, at the time of its expulsion, is in a molten condition. It usually consists of a glassy magma in which, by reason of the high temperature, most or even all of the mineral constituents exist dissolved. Considerable differences, however, have been observed in the degree of liquidity. Humboldt and Scrope long ago called attention to the thick, short, lumpy forms presented by masses of solidified trachytic rocks, which are lighter and more siliceous, and to the thin, widely extended sheets assumed by basalts, which are heavy and contain much iron and basic silicates.[3] It may be inferred that, as a rule, the basalts or basic lavas have been more liquid than the trachytes or siliceous lavas. The cause of this difference has been variously explained. It may depend partly upon chemical composition, the siliceous being naturally less fusible than the basic rocks. But as great differences of fluidity are observable even among lavas having nearly the same composition, there would seem to be some further cause for the diversity. Reyer has ingeniously maintained that we must look to original differences in the extent to which the subterranean igneous magma that supplied the lava has been saturated with vapours and gases. Molten rock highly impregnated gives rise, he holds, to fragmentary discharges, while when feebly impregnated it flows out tranquilly.[4] On the other hand, Captain C. E. Dutton, who has studied the volcanic phenomena of Western America and Hawaii, suggests that the different degrees of liquidity may depend not only on chemical differences, but on variations of temperature. He supposes that the basaltic lavas which have spread so far in thin sheets, and which must have had a comparatively great liquidity, flowed at temperatures far above that of their melting point, and were, to use his phrase, "superfused."[5]

Deutsch. Geol. Ges. xxvi. (1875), p. 36. G. Mercalli, 'Le Eruzioni dell' Isola Vulcano,' *Rassegna Nazionale*, 1889 ; also a paper by same author in *Atti. Soc. Ital. Sci. Nat.*, vol. xxxi.

[1] 'Der Aetna,' ii. 393.

[2] Lyell, 'Principles,' ii. p. 49. Helland, 'Lakis-kratere,' cited *ante*, p. 202.

[3] Scrope, 'Considerations on Volcanoes' (1825), p. 93.

[4] 'Beitrag zur Physik der Eruptionen,' p. 77.

[5] "High Plateaux of Utah," *Geog. and Geol. Sur. Territories*. Washington, 1880, chap. v.

The varying degrees of liquidity are manifested in a characteristic way on the surface of lava. Thus, in the great lava-pools of Hawaii, the rock exhibits a remarkable liquidity, throwing up fountains of molten rock to a height of 300 feet or more. During its ebullition in the crater-pools, jets and dribblets, a quarter of an inch in diameter, are tossed up, and falling back on one another, make "a column of hardened tears of lava," one of which (Fig. 49) was found to have attained a height of 40 feet, while in other places, the jets thrown up and blown aside by the wind give rise to long threads of glass which lie thickly together like mown grass, and are known by the natives under the name of "Pele's Hair," after one of their divinities.[1] Yet although the ebullition is caused by the uprise and escape of highly heated vapours, there is no cloud over the boiling lake itself, heavy white vapour only escaping at different points along the edge.

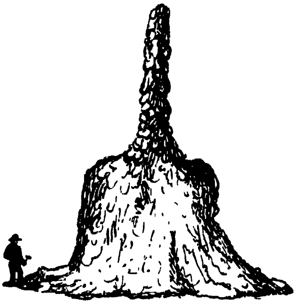
Fig. 49.—Column formed of congealed jets of liquid Lava, Crater of Kilauea (Dana).

On the other hand, the lavas of Vesuvius and of most modern volcanoes, which issue so saturated with vapour as to be nearly concealed from view in a cloud of steam, are accompanied by abundant explosions of fragmentary materials. Slags and clinkers, torn by explosions of steam from the molten rock, are strewn abundantly over the cone, while the surface of the lava is likewise rugged with similar clinkers, which may now and then be observed piled up round some more energetic steam-spiracle. Sometimes the vapour forces up the lava round such a spiracle or fumarole and gradually piles up a rugged column several feet or yards in height, as has been observed on Vesuvius[2] (Figs. 46, 49, 50). So vast an amount of steam rushes out from one of these orifices, and with such boiling and explosion, that the cone of bombs, slags, and irregular lumps of lava forms a miniature or parasitic volcano, which will remain as a marked cone on its parent mountain long after the eruption which gave it birth has ceased. The lava of the eruption at Santorin in 1866-67 at first welled out tranquilly, but after a few days its outflow was accompanied by explosions and discharges of incandescent fragments, which increased until they had covered the lava dome with ejected scoriæ, and had opened a number of crateriform mouths on its summit.[3]

There can be no doubt, as above remarked, that the condition of liquidity of the lava has in some measure determined the form of the eruptions. In one case, there are quiet out-wellings of the more liquid lavas, as at Hawaii; in another, there are explosive discharges and cinder-cones accompanying the more viscid lavas, as at most modern volcanoes. The former has been the condition favourable to the most colossal outpourings of molten rock, as we see in the basalt-plateaux of Britain, Faroe, Greenland, Idaho, and Oregon, the Ghauts, Abyssinia, etc. This subject is again referred to at p. 255.

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[1] Dana, *Geol. U.S. Explor. Exped.*, "Geology," p. 179; 'Characteristics of Volcanoes,' p. 160

[2] Some good examples were observed on this mountain in the summer of 1891 by Mr. Johnston-Lavis, *Brit Assoc.* 1891, sect. C.

[3] Fouqué, 'Santorin,' p. xv.

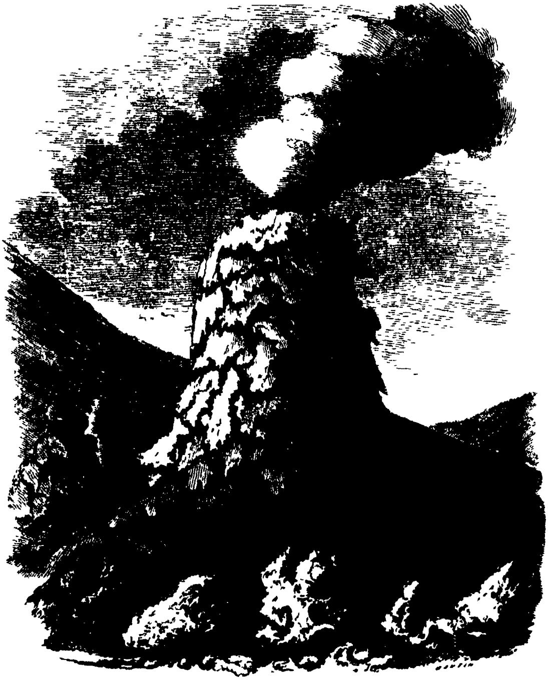

Fig. 50.—Lava-column (eight feet high), Vesuvius (Abich).

Crystallization of Lava.—Pouring forth with a liquidity like that of molten iron, lava speedily assumes a more viscous condition and a slower motion. Obsidian and other vitreous rocks have consolidated as glass: yet that they are not always extremely fluid is indicated by the arrest of the obsidian stream half-way down the steep northern slope of Volcano. Even in such perfect natural glass as obsidian, microscopic crystallites and crystals are usually present, and in prodigious numbers (pp. 115, 162). In most lavas, devitrification has proceeded so far before the final stiffening, that the original glassy magma has passed into a more or less completely lithoid or crystalline mass.

That lava may possess an appreciably crystalline structure while still in motion, has often been proved at Vesuvius, where well-defined crystals of the infusible leucite may be observed in a molten magma of the other minerals, portions of the white-hot rock in this condition being ladled out, impressed with a stamp and suddenly congealed. The fluxion-structure above described (pp. 100, 120) furnishes interesting evidence of this fact in many ancient as well as modern lavas.

There is reason to believe that in the molten magma beneath a volcano considerable progress may be made in the development of some crystalline minerals out of the surrounding glass, and that this crystalline portion *may be to some extent separated from the vitreous residue. Hence where* this has taken place, subsequent eruptions may give rise to a more crystalline and probably more basic lava from one point of emission and a more glassy and probably more acid lava from another vent. Or we may conceive that the two portions of the magma may be subsequently mingled again in various proportions before eruption.[1] If the process of differentiation should continue, as seems natural, during the lapse of a whole cycle of a volcano's history, the earlier lavas would be more basic than the later.

The crystalline structure of lava has been supposed to be in some measure determined by the presence of the volcanic vapours and gases with which the molten rock is impregnated, the rapid escape of these vapours preventing the formation of the crystalline structure, and leaving the lava in the condition of a more or less perfect glass. But the experiments of MM. Fouqué and Michel-Lévy (*postea*, p. 302) have shown that rocks, having in every essential particular the characters of volcanic lavas, may be artificially produced under ordinary atmospheric pressure by simple dry fusion. There appears to be no doubt that the presence of water lowers the fusion-point of silicates, though what precise influence the dissolved vapours exert upon the ultimate consolidation of molten lava has yet to be ascertained. Difference in the rate of cooling has doubtless been an important, if not the main, factor in determining the various conditions of texture of lava-streams. The crystalline structure may be expected to be most perfect where, as within thick masses of rock, the cooling has been prolonged, and where, consequently, the crystals have had ample time and opportunity for their formation. On the other hand, the glassy structure will naturally be most perfectly shown where the cooling has been most rapid, as in the vitreous crust on the walls of dykes already referred to (pp. 171, 210). Rocks crystallizing in the deeper parts of a volcano usually possess a more coarsely crystalline structure than those which crystallize at or near to the surface (p. 564).

Temperature of Lava.—It would be of the highest interest and importance to know accurately the temperature at which a lava-stream first issues. Measurements not altogether satisfactory have been taken at various distances below the point of emission, where the moving lava could be safely approached. Experiments made at Vesuvius by Scacchi and Sainte-Claire Deville in 1855, by thrusting thin wires of silver, iron, and copper into the lava, indicated a temperature of scarcely 700° C. (1228° Fahr.) Observations of a similar kind, made in 1819, when a silver wire $\frac{1}{40}$th inch in diameter at once melted in the Vesuvian lava of that year, gave a greatly higher temperature, the melting-point of silver being about 1800° Fahr. But copper wire has also been melted, the point of fusion of this metal being about 2204° Fahr. Evidence of the high temperature of lava has likewise been adduced from the alteration it has effected upon refractory substances in its progress, as where, at Torre del Greco, it overflowed the houses, and was afterwards found to have fused the fine edges of flints, to have decomposed brass into its component metals, the copper actually crystallizing, and to have melted silver, and even sublimed it into small octahedral crystals (p. 230). The lava of Santorin has caught up pieces of limestone, and has formed out of them nodules containing crystallized anorthite, augite, sphene, black garnet, and particularly wollastonite.[1] . The initial temperature of lava, as it first issues from the Vesuvian funnel, is probably considerably more than 2000° Fahr. Obviously the dissolved water (or water-substance, for, as already remarked, the temperature is far above the critical point of water, and its component gases may exist dissociated) must possess as high a temperature as that of the white-hot lava in which it is contained. The existence of the elements of water at a white heat, even in rocks which have reached the surface, is a fact of no little significance in the theoretical consideration of hypogene action.

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[1] Compare the observation of Ch. Vélain cited *ante*, p. 219, and the remarks *postea*, pp. 262, 269, 564. Consult on this subject a paper by Prof. Judd, *Geol. Mag.* 1888, p. 1.

Inclination and thickness of lava-flows.—It was at one time supposed that lava could not consolidate in beds on such steep slopes as those of most volcanoes. Hence arose the "elevation-crater theory" (described at p. 241), in which the inclined position of lavas round a volcanic vent was explained by upheaval after their emission. Observations all over the world, however, have now demonstrated that lava, with all its characteristic features, can consolidate on slopes of even 35° and 40°.[2] The lava in the Hawaii Islands has cooled rapidly on slopes of 25°, that from Vesuvius, in 1855, is here and there as steep as 30°, while the older lavas in Monte Somma are sometimes inclined at 45°. On the east side of Etna, a cascade of lava, which in 1689 poured into the vast hollow of the Cava Grande, has an inclination varying from 18° to 48°, with an average thickness of 16 feet. On Mauna Loa some lava-flows are said to have congealed on slopes of 49°, 60°, and even 90°,[3] though in these cases it could only be a layer of rock, stiffening and adhering to the surface of the declivity. On the other hand, lava-streams have travelled considerable distances over ground that to the eye looks quite level. Among the Hawaiian islands a declivity of 1° or less has been quite sufficient for the flow of the extremely liquid and mobile lavas of that region. In the great lava-fields of the Snake River region of the Western Territories of the United States the basalts, which must also have been extremely liquid, have flowed over slopes of much less than 1°.[4] The breadth and length of a lava-stream, as well as the form of its surface, depend mainly upon the liquidity of the molten material at the time of outflow. Even when it consolidates on a steep slope, a stream of lava forms a sheet with parallel upper and under surfaces, a general uniformity of thickness, and often greater evenness of surface, than where the angle of descent is low. The thickness varies indefinitely; many basalts which have been poured out in a remarkably liquid condition have solidified in beds not more than 10 or 12 feet thick. On the other hand, more pasty lavas, and lavas which have flowed into narrow valleys, may be piled up in solid masses to a thickness of several hundred feet (pp. 222, 229).

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[1] Fouqué, 'Santorin,' p. 206.

[2] Lyell on the consolidation of lava on steep slopes, *Phil. Trans.* 1858.

[3] J. D. Dana. *Amer. Jour. Sci.* xxxv. (1888), p. 32.

[4] J. D. Dana, 'Characteristics of Volcanoes,' p. 12.

Structure of a lava-stream.—Lava-streams are sometimes nearly homogeneous throughout. In general, however, they each show three component layers. At the bottom lies a rough, slaggy mass, produced by the rapid cooling of the lava, and the breaking up and continued onward motion of the scoriform layer. The central and main portion of the stream consists of solid lava, often, however, with a more or less carious and vesicular texture. The upper part, as we have seen, may be a mass of rough broken-up slabs, scoriæ, or clinkers. The proportions borne by these respective layers to each other vary continually. Some of the more fluid ropy lavas of Vesuvius have an inconstant and thin slaggy crust; others may be said to consist of little else than scoriæ from top to bottom. Throughout the whole mass of a lava-current, but more especially along its upper surface, the absorbed or dissolved water-vapour expands with diminution of pressure, and pushing the molten rock aside, segregates into small bubbles or irregular cavities. Hence, when the lava solidifies, these steam-holes are seen to be sometimes so abundant that a detached portion of the rock containing them will float in water (pumice). They are often elongated in the direction of the motion of the lava-stream (Fig. 51). Sometimes, indeed, where the cells are numerous, their elongation in one direction gives a fissile structure to the rock.

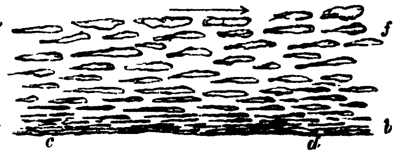

Fig. 51.—Elongation of vesicles in direction of flow of lava.

A singular feature in many lava-streams are the tunnels and caverns already referred to (p. 221) as observable in them. These cavities have doubtless arisen during the flow of the mass when the upper and under portions had solidified and were creeping sluggishly onward, while the still molten interior was able to move faster and thus to leave empty spaces behind it. Such tunnels may frequently be seen among the Vesuvian lava-streams. Some remarkable examples are described from the highly glassy lavas of Hawaii, where they are sometimes from 2 to 10 feet in height and 30 feet broad, but with large lateral expansions. The walls of these Hawaiian lava-chambers are smooth and even glassy, and from their roofs hang slender stalactites of lava 20 to 30 inches long, while on the floor below little mounds of lava-stalagmite have formed. The precise mode of origin of these curious appendages is not yet understood.[1]

In passing from a fluid to a solid condition, and thus contracting, lava acquires different structures. Lines of divisional planes or joints traverse it, especially perpendicular to the upper and under surfaces of the sheet. These sometimes assume prismatic forms, dividing the rock into columns, as is so frequently to be observed in basalt. They are described in Book IV. Part II., together with other forms of joints.

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[1] See Dana's 'Characteristics of Volcanoes,' pp. 209, 332.

Vapours and sublimations of a lava-stream.—Besides steam, many other vapours, absorbed in the original subterranean molten magma, escape from the fissures of a lava-stream. Such vapours are copiously disengaged at *fumaroles* (pp. 194, 195). Among the exhalations, chlorides abound, particularly chloride of sodium, which appears, not only in fissures, but even over the cooled crust of the lava, in small crystals, in tufts, or as a granular and even glassy incrustation. Chloride of iron is deposited as a yellow coating at fumaroles, where also bright emerald-green films and scales of chloride of copper may be more rarely observed. Many chemical changes take place in the escape of these vapours. Thus specular-iron, either the result of the mutual decomposition of steam and iron-chloride, or of the oxidation of magnetite, forms abundant scales, plates, and small crystals in the fumaroles and vesicles of some lavas. Sal-ammoniac also appears in large quantity on many lavas, not merely in the fissures, but also on the upper surface. In these cases, it is not directly a volcanic product, but results from some decomposition, possibly from the gases evolved by the sudden destruction of vegetation. It has, however, been observed also in the crater of Etna, where the co-operation of organic substance is hardly conceivable, and where perhaps it may arise from the decomposition of aqueous vapour, whereby a combination is formed with atmospheric nitrogen. Sulphur, breislakite, szaboite, tenorite, alum, sulphates of iron, soda and potash, and other minerals are also found.

Slow cooling of lava.—The hardened crust of a lava-stream is a bad conductor of heat. Consequently, the surface of the stream may have become cool enough to be walked upon, though the red-hot mass may be observed through the rents to lie only a few inches below. Many years, therefore, may elapse before the temperature of the whole mass has fallen to that of the surrounding soil. Eleven months after an eruption of Etna, Spallanzani could see that the lava was still red-hot at the bottom of the fissures, and a stick thrust into one of them instantly took fire. The Vesuvian lava of 1785 was found by Breislak, seven years afterwards, to be still hot and steaming internally, though lichens had already taken root on its surface. The ropy lava erupted by Vesuvius in 1858 was observed by the author in 1870 to be still so hot, even near its termination, that steam issued abundantly from its rents, many of which were too warm to allow the hand to be held in them, and three years later it was still steaming abundantly. Hoffmann records that from the lava which flowed from Etna in 1787, steam was still issuing in 1830. Yet more remarkable is the case of Jorullo, in Mexico, which sent out lava in 1759. Twenty-one years later a cigar could be lighted at its fissures; after 44 years it was still visibly steaming; and even in 1846, that is, after 87 years of cooling, two vapour-columns were still rising from it.[1]

This extremely slow rate of cooling has justly been regarded as a point of high geological significance, in regard to the secular cooling and probable internal temperature of our globe. Some geologists have argued, indeed, that if so comparatively small a portion of molten matter as a lava-stream can maintain a high temperature under a thin, cold crust for so many years, we may, from analogy, feel little hesitation in believing that the enormously vaster mass of the globe may, beneath a relatively thin crust, still continue in a molten condition within. More legitimate deductions, however, might be drawn from more accurate and precise measurements of the rate of loss of heat, and of its variations in different lava-streams. Lord Kelvin, for instance, has suggested that, by measuring the temperature of intrusive masses of igneous rock in coal-workings and elsewhere, and comparing it with that of other non-volcanic rocks in the same regions, we might obtain data for calculating the time which has elapsed since these igneous sheets were erupted (*ante*, p. 50).

Effects of lava-streams on superficial waters and topography.—In its descent, a stream of lava may reach a water-course, and, by throwing itself as an embankment across the stream, may pond back the water and form a lake. Such is the origin of the picturesque Lake Aidat in Auvergne. Or the molten current may usurp the channel of the stream, and completely bury the whole valley, as has happened again and again among the vast lava-fields of Iceland. Few changes in physiography are so rapid and so enduring as this. The channel which has required, doubtless, many thousands of years for the water laboriously to excavate, is sealed up in a few hours under 100 feet or more of stone, and another vastly protracted interval may elapse before this newer pile is similarly eroded.[2]

By suddenly overflowing a brook or pool of water, molten lava sometimes has its outer crust shattered to fragments by a sharp explosion of the generated steam, while the fluid mass within rushes out on all sides.[3] The lava emitted by Mauna Loa, Hawaii, in the spring of 1868 flowed out to sea, and added half a mile to the extent of the island at that point. At the end of the stream three cinder-cones formed from the contact of the lava with the water, and Captain Dutton calls special attention to the fact that not only in this instance, but in other examples among the Hawaiian lavas which have reached the sea, there is clear evidence of the formation of ordinary volcanic craters by the accidental contact of lava with water.[4] The lavas of Etna and Vesuvius have also protruded into the sea, but, owing probably to their more viscous and lithoid condition and lower temperature, they do not seem to have given rise to explosive action at their seaward ends. Thus a current from the latter mountain entered the Mediterranean at Torre del Greco in 1794, and pushed its way for 360 feet outwards, with a breadth of 1100 and a height of 15 feet. So quietly did it advance, that Breislak could sail round it in a boat and observe its progress.

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[1] E. Schleiden, quoted by Naumann, 'Geognosie,' i. p. 160.

[2] For an example of the conversion of a lava-buried river-bed into a hill-top by long-continued denudation, see *Quart. Journ. Geol. Soc.* 1871, p. 303.

[3] Explosions of this nature have been observed on Etna, where the lava has suddenly come in contact with water or snow, considerable loss of life being sometimes the result. Sartorius von Waltershausen and A. von Lasaulx, 'Der Aetna,' i. pp. 295, 300

[4] *U.S. Geol. Report for* 1882-83, p. 181.

By the outpouring of lava, two important kinds of geological change are produced. (1) Stream-courses, lakes, ravines, valleys, in short, all the minor features of a landscape, may be completely overwhelmed under a thick sheet of lava. The drainage of the district being thus effectually altered, the numerous changes which flow from the operations of running water over the land are arrested and made to begin again in new channels. (2) Considerable alterations may likewise be caused by the effects of the heat and vapours of the lava upon the subjacent or contiguous ground. Instances have been observed in which the lava has actually melted down opposing rocks, or masses of slags on its own surface. Interesting observations, already referred to (p. 226), have been made at Torre del Greco under the lava-stream which overflowed part of that town in 1794. It was found that the window-panes of the houses had been devitrified into a white, translucent, stony substance; that pieces of limestone had acquired an open, sandy, granular texture, without loss of carbon-dioxide, and that iron, brass, lead, copper, and silver objects had been greatly altered, some of the metals being actually sublimed. We can understand, therefore, that, retaining its heat for so long a time, a mass of lava may induce many crystalline structures, rearrangements, or decompositions in the rocks over which it comes to rest, and proceeds slowly to cool. This is a question of considerable importance in relation to the behaviour of ancient lavas which after having been intruded among rocks beneath the surface, have subsequently been exposed by denudation (Book IV. Part VII.)

But on the other hand, the exceedingly trifling change produced, even by a massive sheet of lava, has often been remarked with astonishment. On the flank of Vesuvius, vines and trees may be seen still flourishing on little islets of the older land-surface, completely surrounded by a flood of lava. Dana has given an instructive account of the descent of a lava-stream from Kilauea in June 1840. Islet-like spaces of forest were left in the midst of the lava, many of the trees being still alive. Where the lava flowed round the trees, the stumps were usually consumed, and cylindrical holes or casts remained in the lava, either empty or filled with charcoal. In many cases, the fallen crown of the tree lay near, and so little damaged that the epiphytic plants on it began to grow again. Yet so fluid was the lava that it hung in pendent stalactites from the branches, which nevertheless, though clasped round by the molten rock, had barely their bark scorched. Again, for nearly 100 years there has lain on the flank of Etna a large sheet of ice, which, originally in the form of a thick mass of snow, was overflowed by lava, and has thereby been protected from the evaporation and thaw which would certainly have dissipated it long ago, had it been exposed to the air. The heat of the lava has not sufficed to melt it. Extensive tracts of snow were likewise overspread by lava from the same mountain in 1879. In other cases, snow and ice have been melted in large quantities by overflowing lava. The great floods of water which rushed down the flank of Etna, after an eruption of the mountain in the spring of 1755, and similar deluges at Cotopaxi, are thus explained.

One further aspect of a lava-stream may be noticed here—the effect of time upon its surface. While all kinds of lava must, in the end, crumble down under the influence of atmospheric waste and, where other conditions permit, become coated with soil, and support some kind of vegetation, yet extraordinary differences may be observed in the facility with which different lava-streams yield to this change, even on the flank of the same mountain. Every one who ascends the slopes of Vesuvius remarks this fact. After a little practice, it is not difficult there to trace the limits of certain lavas even from a distance, in some cases by their verdure, in others by their barrenness. Five hundred years have not sufficed to clothe with green the still naked surface of the Catanian lava of 1381; while some of the lavas of the present century have long given footing to bushes of furze.[1] Some of the younger lavas of Auvergne, which certainly flowed in times anterior to those of history, are still singularly bare and rugged. Yet, on the whole, where lava is directly exposed to the atmosphere, without receiving protection from occasional showers of volcanic ash, or where liable to be washed bare by heavy torrents of rain, its surface decays in a few years sufficiently to afford soil for stray plants in the crevices. When these have taken root they help to increase the disintegration; at last, as the rock is overspread, the traces of its volcanic origin fade away from its surface. Some of the Vesuvian lavas of the present century already support vineyards.

Elevation and Subsidence.—Proofs of elevation are frequent among volcanic vents which, lying near the sea and containing marine sediments among their older erupted materials, supply, in the enclosed marine organisms, evidence of the movement. In this way, it is known that Etna, Vesuvius, and other Mediterranean volcanoes, began their history as submarine vents, and that they owe their present dimensions not only to the accumulation of ejected materials, but also, to some extent, to an elevation of the sea-bottom.

Proof of subsidence is less easily traced, but indications have been observed of a sinking of the ground beneath a volcanic vent. During the eruption of Santorin in 1866-67, very decided but extremely local subsidence took place near the vent in the centre of the old crater. The discharge of such prodigious quantities of material may tend to produce cavernous spaces in the terrestrial crust, and the weight of the ejected lavas and tuffs may still further contribute to a general settlement of the ground around a volcanic focus.

If we consider the records of volcanic action in past geological time we meet with many proofs that it took place in areas where the predominant terrestrial movement was one of subsidence. Thus among the Palæozoic systems of Britain the Cambrian, Silurian, Devonian, Carboniferous, and Permian volcanoes successively appeared, and their lavas and tuffs were carried down and buried under thousands of feet of sedimentary deposits.[1]

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[1] On the weathering of the Etna lavas, see 'Der Aetna,' ii. p. 397.

Torrents of Water and Mud.—We have seen that large quantities of water accompany many volcanic eruptions. In some cases, where ancient crater-lakes or internal reservoirs, shaken by repeated detonations, have been finally disrupted, the mud which has thereby been liberated has issued from the mountain. Such "mud-lava" (*lava d'acqua*), on account of its liquidity and swiftness of motion, is more dreaded for destructiveness than even the true melted lavas. On the other hand, rain or melted snow or ice, rushing down the cone and taking up loose volcanic dust, is converted into a kind of mud that grows more and more pasty as it descends. The mere sudden rush of such large bodies of water down the steep declivity of a volcanic cone cannot fail to effect much geological change. Deep trenches are cut out of the loose volcanic slopes, and sometimes large areas of woodland are swept away, the débris being strewn over the plains below.

One of these mud-lavas invaded Herculaneum during the great eruption of 79, and by quickly enveloping the houses and their contents, has preserved for us so many precious and perishable monuments of antiquity. In the same district, during the eruption of 1622, a torrent of this kind poured down upon the villages of Ottajano and Massa, overthrowing walls, filling up streets, and even burying houses with their inhabitants. During the great eruption of Cotopaxi, in June 1877, enormous torrents of water and mud, produced by the melting of the snow and ice of the cone, rushed down from the mountain. Huge portions of the glaciers of the mountain were detached by the heat of the rocks below them and rushed down bodily breaking up into blocks. The villages all round the mountain to a distance of sometimes more than ten geographical miles were left deeply buried under a deposit of mud mixed with blocks of lava, ashes, pieces of wood, lumps of ice, &c.[2] Many of the volcanoes of Central and South America discharge large quantities of mud directly from their craters. Thus, in the year 1691, Imbaburu, one of the Andes of Quito, emitted floods of mud so largely charged with dead fish that pestilential fevers arose from the subsequent effluvia. Seven years later (1698), during an explosion of another of the same range of lofty mountains, Carguairazo (14,706 feet), the summit of the cone is said to have fallen in, while torrents of mud containing immense numbers of the fish *Pymelodus Cyclopum*, poured forth and covered the ground over a space of four square leagues. The carbonaceous mud (locally called *moya*) emitted by the Quito volcanoes sometimes escapes from lateral fissures, sometimes from the craters. Its organic contents, and notably its siluroid fish, which are the same as those found living in the streams above ground, prove that the water is derived from the surface, and accumulates in craters or underground cavities until discharged by volcanic action. Similar but even more stupendous and destructive outpourings have taken place from the volcanoes of Java, where wide tracts of luxuriant vegetation have at different times been buried under masses of dark grey mud, sometimes 100 feet thick, with a rough hillocky surface from which the top of a submerged palm-tree would here and there protrude.

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[1] Presidential Addresses, *Quart. Journ. Geol. Soc.* xlvii. (1891), xlviii. (1892).

[2] Wolf, *Neues Jahrb.* 1878, p. 133.

Between the destructive effects of mere water-torrents and that of these mud-floods there is, of course, the notable difference that, whereas in the former case a portion of the surface is swept away, in the latter, while sometimes considerable demolition of the surface takes place at first, the main result is the burying of the ground under a new tumultuous deposit by which the typography is greatly changed, not only as regards its temporary aspect, but in its more permanent features, such as the position and form of its water-courses.

Effects of the Closing of a Volcanic Chimney—Sills and Dykes.—A study of the volcanic phenomena of former geological periods, where the structure of the interior of volcanoes and their funnels has been laid bare by denudation, shows that in many cases a vent becomes plugged up by the ascent and consolidation of solid material in it, while yet the eruptive energy of the volcano, though lessened, has not ceased. A time is reached when the ascending magma, impelled by pressure from below, can no longer overcome the resistance of the column of solid lava or compacted agglomerate which has sealed up the orifice of discharge, or at least when it can more easily force a passage for itself between the sedimentary strata on which the whole volcanic pile may rest, or between the lava sheets at the base of the pile, or into fissures in either or both of these groups. Hence arise intrusive sheets or sills and dykes or veins (see pp. 573, 577). That these later manifestations of volcanic energy have sometimes taken place on a great scale is shown by the number and size of the sills which are found at the base of the Palæozoic volcanic groups of Britain. This feature is a remarkably striking feature of the rocks that underlie the great Lower Silurian volcanic outflows of Arenig and Cader Idris in North Wales. It recurs so frequently, not only among Palæozoic volcanic phenomena but quite as markedly among those of Tertiary age in the British Isles, that it must be regarded as marking an ordinary phase of volcanic action. But it remains of course invisible until in the progress of denudation a volcanic cone is cut down to the roots.

Exhalations of Vapours and Gases.—A volcano, as its activity wanes, may pass into the Solfatara stage, when only volatile emanations are discharged. The well-known Solfatara near Naples, since its last eruption in 1198, has constantly discharged steam and sulphurous vapours. The island of Volcano has now passed also into this phase, though giving vent to occasional explosions. Numerous other examples occur among the old volcanic tracts of Italy, where they have been termed *soffioni*. Steam, escaping in conspicuous jets, sulphuretted hydrogen, hydrochloric acid, and carbonic acid are particularly noticeable at these orifices. The vapours in rising condense. The sulphuretted hydrogen partially oxidises into sulphuric acid, which powerfully corrodes the surrounding rocks. The lava or tuff through which the hot vapours rise is bleached into a white or yellowish crumbling clay, in which, however, the less easily corroded crystals may still be recognised *in situ.* At the same time, sublimates of sulphur or of chlorides may be formed, or the sulphuric acid attacking the lime of the silicates gives rise to gypsum, which spreads in a network of threads and veins through the hot, steaming, and decomposed mass. In this way, at the island of Volcano, obsidian is converted into a snow-white, dull, clay-stone-like substance, with crystals of sulphur and gypsum in its crevices. Silica is likewise deposited from solution at many orifices, and coats the altered rock with a crust of chalcedony, hyalite, or some form of siliceous sinter. As the result of this action, masses of rock are decomposed below the surface, and new deposits of alum, sulphur, sulphides of iron and copper, &c., are formed above them. Examples have been described from Iceland, Lipari, Hungary, Terceira, Teneriffe, St. Helena, and many other localities.[1] The *lagoons* of Tuscany are basins into which the waters from suffioni are discharged, and where a precipitation of their dissolved salts takes place. Among the substances thus deposited are gypsum, sulphur, silica, and various alkaline salts; but the most important is boracic acid, the extraction of which constitutes a thriving industry. In Chili many solfataras occur among extinct volcanoes.[2]

Another class of gaseous emanations betokens a condition of volcanic activity further advanced towards final extinction. In these, the gas is carbon-dioxide, either issuing directly from the rock or bubbling up with water which is often quite cold. The old volcanic districts of Europe furnish many examples. Thus on the shores of the Laacher See—an ancient crater-lake of the Eifel—the gas issues from numerous openings called *moffette,* round which dead insects, and occasionally mice and birds, may be found. In the same region occur hundreds of springs more or less charged with this gas. The famous Valley of Death in Java contains one of the most remarkable gas-springs in the world. It is a deep, bosky hollow, from one small space on the bottom of which carbon-dioxide issues so copiously as to form the lower stratum of the atmosphere. Tigers, deer, and wild-boar, enticed by the shelter of the spot, descend and are speedily suffocated. Many skeletons, including those of man himself, have been observed.

As a distinct class of gas-springs, we may group and describe here the emanations of volatile hydrocarbons, which, when they take fire, are known as Fire-wells. These are not of volcanic origin, but arise from changes within the solid rocks underneath. They occur in many of the districts where mud-volcanoes appear, as in northern Italy, on the Caspian, in Mesopotamia, in southern Kurdistan, and in many parts of the United States. It has been observed that they frequently rise in regions where beds of rock-salt lie underneath, and as that rock has been ascertained often to contain compressed gaseous hydrocarbons, the solution of the rock by subterranean water, and the consequent liberation of the gas, has been offered as an explanation of these fire-wells.

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[1] Von Buch, 'Canar. Inseln,' p. 232. Hoffmann, *Pogg. Ann.* 1832, pp. 38, 40, 60. Bunsen, *Ann. Chem. Pharm.* 1847 (lxii.), p. 10. Darwin, 'Volcanic Islands,' p. 29. The name *Propylite,* as already mentioned (*ante,* p. 169) has been proposed by Rosenbusch to be restricted to certain andesites and allied rocks altered by solfataric action.

[2] Domeyko, *Ann. Mines,* ix. (7e sér.) Large numbers of solfataras occur also in Iceland.

In the oil regions of Pennsylvania, certain sandy strata occur at various geological horizons whence large quantities of petroleum and gas are obtained (p. 145). In making the borings for oil-wells, reservoirs of gas as well as subterranean courses or springs of water are met with. When the supply of oil is limited but that of gas is large, a contest for possession of the bore-hole sometimes takes place between the gas and water. When the machinery is removed and the boring is abandoned, the contest is allowed to proceed unimpeded and results in the intermittent discharge of columns of water and gas to heights of 130 feet or more. At night, when the gas has been lighted, the spectacle of one of these "fire-geysers" is inconceivably grand.[1]

Geysers.—Eruptive fountains of hot water and steam, to which the general name of Geysers (*i.e.* gushers) is given, from the examples in Iceland, which were the first to be seen and described, mark a declining phase of volcanic activity. The Great and Little Geysers, the Strokkr and other minor springs of hot water in Iceland, have long been celebrated examples. More recently another series has been discovered in New Zealand. But probably the most remarkable and numerous assemblage is that which has been brought to light in the north-west part of the territory of Wyoming, and which has been included within the "Yellowstone National Park"—a region set apart by the Congress of the United States to be for ever exempt from settlement, and to be retained for the instruction of the people. In this singular region the ground in certain tracts is honeycombed with passages which communicate with the surface by hundreds of openings, whence boiling water and steam are emitted. In most cases, the water remains clear, tranquil, and of a deep green-blue tint, though many of the otherwise quiet pools are marked by patches of rapid ebullition. These pools lie on mounds or sheets of sinter, and are usually edged round with a raised rim of the same substance, often beautifully fretted and streaked with brilliant colours. The eruptive openings usually appear on small, low, conical elevations of sinter, from each of which one or more tubular projections rise. It is from these irregular tube-like excrescences that the eruptions take place.

The term geyser is restricted to active openings whence columns of hot water and steam are from time to time ejected; the non-eruptive pools are only hot springs. A true geyser should thus possess an underground pipe or passage, terminating at the surface in an opening built round with deposits of sinter. At more or less regular intervals, rumblings and sharp detonations in the pipe are followed by an agitation of the water in the basin, and then by the violent expulsion of a column of water and steam to a considerable height in the air. In the Upper Fire Hole basin of the Yellowstone Park, one of the geysers, named "Old Faithful" (Fig. 52), has ever since the discovery of the region, sent out a column of mingled water and steam every sixty-three minutes or thereabouts. The column rushes up with a loud roar to a height of more than 100 feet, the whole eruption not occupying more than about five or six minutes. The other geysers of the same district are more capricious in their movements, and some of them more stupendous in the volume of their discharge The eruptions of the Castle, Giant, and Beehive vents are marvellously impressive[1]

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[1] Ashburner, *Proc. Amer. Phil. Soc.* xvii. (1877), p. 127. *Stowell's Petroleum Reporter*, 15th Sept. 1879. *Second Geol. Survey of Pennsylvania*, containing Reports by J. Carll, 1877, 1880. J. S. Newberry, 'The First Oil Well.' Harper's Magazine, Oct. 1890. On the naphtha districts of the Caspian Sea, Abich, *Jahrb. Geol. Reichs.* xxix. (1879), p. 165. H. Sjögren, *op. cit.* xxxvii. (1887), p. 47. C. Marvin, 'Region of Eternal Fire,' London, 1884. See also for phenomena in Gallicia, *Jahrb. Geol. Reichs.* xv. pp. 199, 351; xvii. p. 291; xviii. p. 311; xxxi. (1881), p. 131. *Proc. Inst. Civ. Engineers*, xlii. (1875), p. 343.

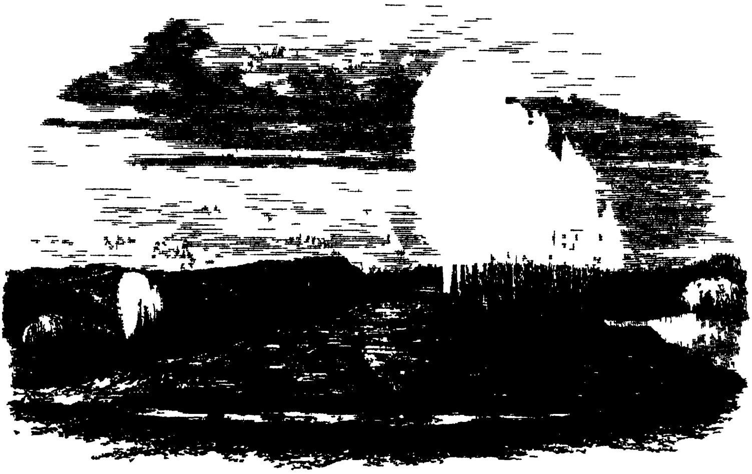

Fig 52 View of Old Faithful Geyser, and others in the distance, Fire Hole River, Yellowstone Park

In examining the Yellowstone Geyser region in 1879, the author was specially struck by the evident independence of the vents This was shown by their very different levels, as well as by their capricious and unsympathetic eruptions. On the same hill-slope, dozens of quiet pools, as well as some true geysers, were noticed at different levels, from the edge of the Fire Hole River up to a height of at least 80 feet above it Yet the lower pools, from which, of course, had there been underground connection between the different vents, the drainage should have principally discharged itself, were often found to be quiet steaming pools without outlet, while those at higher points were occasionally in active eruption. It seemed also to make no difference in the height or tranquillity of one of the quietly boiling cauldrons, when an active projection of steam and water was going on from a neighbouring vent on the same gentle slope.

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[1] See Hayden's Reports for 1870 and for 1878, in the latter of which will be found a voluminous monograph on the Hot Springs by A C. Peale ; Comstock's Report in Jones's Reconnaissance of N.W. Wyoming, &c , 1874. The deposits of hot springs are further referred to on pp. 153, 483.

Bunsen and Descloiseaux spent some days experimenting at the Icelandic geysers, and ascertained that in the Great Geyser, while the surface temperature is about 212° Fahr., that of lower portions of the tube is much higher—a thermometer giving as high a reading as 266° Fahr. The water at a little depth must consequently be 54° above the normal boiling-point, but it is kept in the fluid state by the pressure of the overlying column. At the basin, however, the water cools quickly. After an explosion it accumulates there, and eventually begins to boil. The pressure on the column below being thus relieved, a portion of the superheated water flashes into steam, and as the change passes down the pipe, the whole column of water and steam rushes out with great violence. The water thereafter gradually collects again in the pipe, and after an interval of some hours the operation is renewed. The experiments made by Bunsen proved the source of the eruptive action to lie in the hot part of the pipe. He hung stones by strings to different depths in the funnel of the geyser, and found that only those in the higher part were cast out by the rush of water, sometimes to a height of 100 feet, while, at the same time, the water at the bottom was hardly disturbed at all. These observations give much interest and importance to the phenomena of geysers in relation to volcanic action. They show that the eruptive force in geysers is steam; that the water column, even at a comparatively small depth, may have a temperature considerably above 212°; that this high temperature is local; and that the eruptions of steam and water take place periodically, and with such vigour as to eject large stones to a height of 100 feet.[1]

The hot water comes up with a considerable percentage of mineral matter in solution. According to the analysis of Sandberger, water from the Great Geyser of Iceland contains in 10,000 parts the following proportions of ingredients: silica, 5·097; sodium-carbonate, 1·939; ammonium-carbonate, 0·083; sodium-sulphate, 1·07; potassium-sulphate, 0·475; magnesium-sulphate, 0·042; sodium-chloride, 2·521; sodium-sulphide, 0·088; carbonic acid, 0·557 = 11·872.[2]

When the water has reached the surface, it deposits the silica as a sinter on the surfaces over which it flows or on which it rests.[1] The deposit, which is not due to mere cooling and evaporation, is curiously aided by the presence of living algæ (*postea*, p. 483). It naturally takes place fastest along the margins of the pools. Hence the curiously fretted rims by which these sheets of water are surrounded, and the tubular or cylindrical protuberances which rise from the growing domes. Where numerous hot springs have issued along a slope, a succession of basins gives a curiously picturesque terraced aspect to the ground, as at the Mammoth Springs of the Yellowstone Park and at the now destroyed terraces of Rotamahana in New Zealand.

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[1] *Comptes Rendus*, xxiii. (1846), p. 934; *Pogg. Annal.* lxxii. (1847), p. 159; lxxxiii. (1851), p. 197. *Ann. Chimie*, xxxviii. (1853), pp. 215, 385. The explanation proposed for the phenomena observed at the Great Geyser is probably not applicable in those cases where the mere local accumulation of steam in suitable reservoirs may be sufficient.

[2] *Annal. Chem. und Pharm.* 1847, p. 49. A series of detailed analyses of the hot springs of the Yellowstone National Park will be found in No. 47 of the *Bull. U.S. Geol. Surv.* 1888.

In course of time, the network of underground passages undergoes alteration. Orifices that were once active cease to erupt, and even the water fails to overflow them. Sinter is no longer formed round them, and their surfaces, exposed to the weather, crack into fine shaly rubbish like comminuted oyster-shells. Or the cylinder of sinter grows upward until, by the continued deposit of sinter and the failing force of the geyser, the tube is finally filled up, and then a dry and crumbling white pillar is left to mark the site of the extinct geyser.

Mud-Volcanoes.—These are of two kinds: 1st, where the chief source of movement is the escape of gaseous discharges; 2nd, where the active agent is steam.

(1) Although not volcanic in the proper sense of the term, certain remarkable orifices of eruption may be noticed here, to which the names of *mud-volcanoes*, *salses*, *air-volcanoes*, and *maccalubas* have been applied (Sicily, the Apennines, Caucasus, Kertch, Taman). These are conical hills formed by the accumulation of fine and usually saline mud, which, with various gases, is continuously or intermittently given out from the orifice or crater in the centre. They occur in groups, each hillock being sometimes less than a yard in height, but ranging up to elevations of 100 feet or more. Like true volcanoes, they have their periods of repose, when either no discharge takes place at all, or mud oozes out tranquilly from the crater, and their epochs of activity, when large volumes of gas, and sometimes columns of flame, rush out with considerable violence and explosion, and throw up mud and stones to a height of several hundred feet. The gases play much the same part, therefore, in these phenomena that steam does in those of true volcanoes. They consist of marsh-gas and other hydrocarbons, carbon-dioxide, sulphuretted hydrogen, and nitrogen, with petroleum vapours. The mud is usually cold. In the water occur various saline ingredients, among which common salt generally appears; hence the name, *Salses*. Naphtha is likewise frequently present. Large pieces of stone, differing from those in the neighbourhood, have been observed among the ejections, indicative doubtless of a somewhat deeper source than in ordinary cases. Heavy rains may wash down the minor mud-cones and spread out the material over the ground; but gas-bubbles again appear through the sheet of mud, and by degrees a new series of mounds is once more thrown up.

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[1] For an account of the geyserite of the Yellowstone district, see papers by W. H. Weed, *Amer. Journ. Sci.* xxxvii. (1889), and 9*th Ann. Rep. U.S. Geol. Surv.* 1890.

There can be little doubt that this type of mud-volcano is to be traced to chemical changes in progress underneath. Dr. Daubeny explained them in Sicily by the slow combustion of beds of sulphur. The frequent occurrence of naphtha and of inflammable gas points, in other cases, to the disengagement of hydrocarbons from subterranean strata.[1]

(2) The second class of mud-volcano presents itself in true volcanic regions, and is due to the escape of hot water and steam through beds of tuff or some other friable kind of rock. The mud is kept in ebullition by the rise of steam through it. As it become more pasty and the steam meets with greater resistance, large bubbles are formed which burst, and the more liquid mud from below oozes out from the vent. In this way, small cones are built up, many of which have perfect craters atop. In the Geyser tracts of the Yellowstone region, there are instructive examples of such active and extinct mud-vents. Some of the extinct cones there are not more than a foot high, and might be carefully removed as museum specimens.

Mud-volcanoes occur in Iceland, Sicily (Maccaluba), in many districts of northern Italy, at Tamar and Kertch, at Baku on the Caspian, near the mouth of the Indus, and in other parts of the globe.[2]

§ 3. Structure of Volcanoes.

We have now to consider the manner in which the various solid materials ejected by volcanic action are built up at the surface. This inquiry will be restricted here to the phenomena of modern volcanoes, including the active and dormant, or recently extinct, phases. Obviously, however, in a modern volcano we can study only the upper and external portions, the deeper and fundamental parts being still concealed from view. But the interior structure has been, in many cases, laid open among the volcanic products of ancient vents. As these belong to the architecture of the terrestrial crust, they are described in Book IV. The student is therefore requested to take the descriptions there given, in connection with the foregoing and present sections, as related chapters of the study of volcanism.

Confining attention at present to modern volcanic action, we find that the solid materials emitted from the earth's interior are arranged in two distinct types of structure, according as the eruptions proceed from large central cones or from less prominent vents connected with fissures. In the former case, volcanic cones are produced; in the latter, volcanic plateaux or plains. The type of the volcanic cone, or ordinary volcano, is now the most abundant and best known.

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[1] The "burning hills" of Turkestan are referred to the subterranean combustion of beds of Jurassic Coal. J. Muschketoff, *Neues Jahrb.* 1876, p. 516.

[2] On mud-volcanoes, see Bunsen, *Liebig's Annual*, lxiii. (1847), p. 1; Abich, *Mem. Acad. St. Petersburg*, 7e sér. t. vi. No. 5, ix. No. 4; Daubeny's *Volcanoes*, pp. 264, 539; Buist, *Trans. Bombay Geograph. Soc.* x. p. 154; Roberts, *Journ. Roy. Asiatic Soc.* 1850. De Verneuil, *Mem. Soc. Géol. France*, iii. (1838), p. 4; Stiffe, *Q. J. Geol. Soc.* xxx. p. 50, Von Lasaulx, *Z. Deutsch. Geol. Ges.* xxxi. p. 457; Gumbel, *Sitzb. Akad. Munch.* 1879; F. R. Mallet, *Rec. Geol. Surv. India*, xi. p. 188. H. Sjogren, *Jahrb. Geol. Reichsanst.* xxxvii. (1887), p. 233.

i. *Volcanic Cones.*

From some weaker point of a fissure, or from a vent opened directly by explosion, volcanic discharges of gas and vapours with their liquid and solid accompaniments make their way to the surface and gradually build up a volcanic hill or mountain. Occasionally, eruptions have proceeded no further than the first stage of gaseous explosion. A cauldron-like cavity has been torn open in the ground, and ejected fragments of the solid rocks, through which the explosion has emerged, have fallen back into and round the vent. Subsequently, after possible subsidence of the fragmentary materials in the vent, and even of the sides of the orifice, water supplied by rain and filtering from the neighbouring ground may partially, or wholly, fill up the cavity, so as to produce a lake either with or without a superficial outlet. Under favourable circumstances, vegetation creeping over bare earth and stone may so conceal all evidence of the original volcanic action as to make the quiet sheet of water look as if it had always been an essential part of the landscape. Explosion-lakes (Crater-lakes) of this kind occur in districts of extinct volcanoes, as in the Eifel (*maare*), central Italy, and Auvergne. The crateriform hollow called the Gour de Tazenat, in Velay, has a diameter of half a mile and lies in the granite, while another cavity near Confolens, on the left bank of the Loire, has also been blown out of the granite and has given passage to no volcanic materials, but only to broken-up granite.[1] Other illustrations in central France are to be found in the Lakes of Pavin, Mont Sineire, Chauvet, Beurdouse, Champedaze and La Godival.[2] A remarkable example is supplied by the Lonar Lake in the Indian peninsula, half-way between Bombay and Nágpúr. It lies in the midst of the volcanic plateau of the Deccan traps, which extend around it for hundreds of miles in nearly flat beds that slightly dip away from the lake. An almost circular depression, rather more than a mile in diameter, and from 300 to 400 feet deep, contains at the bottom a shallow lake of bitter saline water, depositing crystals of trona (native carbonate of soda, the *nitrum* of the ancients). Except to the north and north-east, it is encircled with a raised rim of irregularly piled blocks of basalt, identical with that of the beds through which the cavity has been opened. The rim never exceeds 100 feet, and is often not more than 40 or 50 feet in height, and cannot contain a thousandth part of the material which once filled the crater. No other evidence of volcanic discharge from this vent is to be seen. Some of the contents of the cavity may have been ejected in fine particles, which have subsequently been removed by denudation; but it seems more probable that the existence of the cavity is mainly due to subsidence after the original explosion.[3]

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[1] Tournaire, *Bull. Soc. Géol. France*, xxvi. (1869), p. 1166; Daubrée, *Comptes rend.* 1890, p. 859.

[2] Scrope, 'Volcanoes of Central France,' pp. 81, 143, 144.

[3] This cavity may possibly mark one of the vents from which the basalt floods issued.

In most cases, explosions are accompanied by the expulsion of so much solid material that a cone gathers round the point of emission. As the cone increases in height, by successive additions of ashes or lava to its surface, these volcanic sheets are laid down upon progressively steeper slopes. The inclination of beds of lava, which must have originally issued in a more or less liquid condition, offered formerly a difficulty to observers, and suggested the famous theory of Elevation-craters (*Erhebungskratere*) of L. von Buch,[1] Élie de Beaumont,[2] and other geologists. According to this theory, the conical shape of a volcanic cone arises mainly from an upheaval or swelling of the ground, round the vent from which the materials are finally expelled. A portion of the earth's crust (represented in Fig. 53 as composed of stratified deposits, *a b g h*) was believed to have been pushed up like a huge blister, by forces acting from below (at *c*) until the summit of the dome gave way and volcanic materials were emitted. At first these might only partially fill the cavity (as at *f*), but subsequent eruptions, if sufficiently copious, would cover over the truncated edges of the pre-volcanic rocks (as at *g h*), and would be liable to further upheaval by a renewal of the original upward swelling of the site.

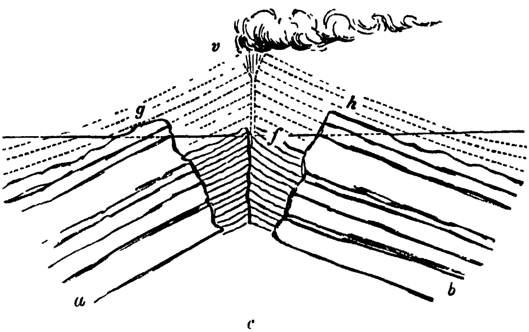

Fig. 53.—Section illustrative of the Elevation-crater Theory.

It was a matter of prime importance in the interpretation of volcanic action to have this question settled. To Poulett Scrope, Constant Prévost, and Lyell, belongs the merit of disproving the Elevation-crater theory. Scrope showed conclusively that the steep slope of the lava-beds of a volcanic cone was original.[3] Constant Prévost pointed out that there was no more reason why lava should not consolidate on steep slopes than that tears or drops of wax should not do so.[4] Lyell, in successive

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On explosion-craters and lakes, see Scrope's 'Volcanoes.' Lecoq, 'Epoques géologiques de l'Auvergne,' tome iv.; compare also Vogelsang, 'Vulcane der Eifel,' and in *Neues Jahrb.* 1870, pp. 199, 326, 460. On Lonar Lake, see Malcolmson, *Trans. Geol. Soc.* 2nd ser. v. p. 562. Medlicott and Blanford's 'Geology of India,' p. 379.

[1] *Pogg. Ann.* ix. x. xxvii. p. 169.

[2] *Bull. Soc. Géol. France*, iv. p. 357. *Ann. des Mines*, ix. and x.

[3] 'Considerations on Volcanoes,' 1825. *Quart. Journ. Geol. Soc.* xii. p. 326.

[4] *Comptes Rendus*, i. (1835), 460; xli. (1855), p. 919. *Géol. Soc. France: Mémoires*, ii. p. 105, and *Bull.* xiv. 217. *Société Philom. Paris*, *Proc. Verb.* 1843, p. 13.

editions of his works, and subsequently by an examination of the Canary Islands with Hartung, brought forward cogent arguments against the Elevation-crater theory.[1] A comparison of Fig. 53 with Fig. 54 will show at a glance the difference between this theory and the views of volcanic structure now universally accepted. The steep declivities on which lava can actually consolidate have been referred to on p. 226.

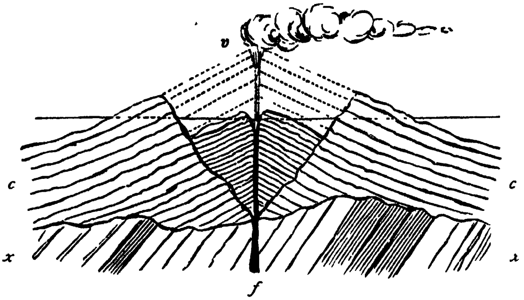

Fig. 54.—Diagram-section of a normal Volcano.

x x, Pre-volcanic platform, supposed here to consist of upraised stratified rocks, broken through by the funnel *f*, from which the cone of volcanic materials *c c* has been erupted. Inside the crater *v*, previously cleared by some great explosion, a minor cone may be formed during feebler phases of volcanic action, and this inner cone may increase in size until the original cone is built up again, as shown by the dotted lines.

The conical form of a volcano is that naturally assumed by a self-supporting mass of coherent material. It varies slightly according to the nature of the materials of the cone, the progress of atmospheric denudation, the position of the crater, the direction in which materials are ejected, the force and direction of the wind during an eruption, the growth of parasitic cones, and the collapse due to the dying out of volcanic energy.[2]

The cone grows by additions made to its surface during successive eruptions, and though liable to great local variation of contour and topography, preserves its general form with singular persistence. Many exaggerated pictures have been drawn of the steepness of slope in volcanic cones, but it is obvious that the angle cannot as a whole exceed the maximum inclination of repose of the detrital matter ejected from the central chimney.[3] A series of profiles of volcanic cones taken from photographs shows how nearly they approach to a common average type.[4] One of the most potent and constant agencies in modifying the outer forms of these cones is undoubtedly to be found in rain and torrents, which sweep down the loose detritus and excavate ravines on the declivities till a cone may be so deeply trenched as to resemble a half-opened umbrella.[1]

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[1] *Phil. Trans.* 1858, p. 703. See the remarks of Fouqué, 'Santorin,' pp. 400-422.

[2] J. Milne, *Geol. Mag.* 1878, p. 339; 1879, p. 506. *Seismolog. Soc. Japan*, ix. p. 179. G. F. Becker, *Amer. Journ. Sci.* xxx. 1885, p. 283.

[3] Cotopaxi is a notable example of such exaggerated representation. Mr. Whymper found that the general angles of the northern and southern slopes of the cone were rather less than 30° ('Travels Amongst the Great Andes,' p. 123). Humboldt depicted the angle as one of 50°!

[4] See Milne, *Seism. Soc. Japan*, ix., and *Geol. Mag.* 1878, plate ix.

The crater doubtless owes its generally circular form to the equal expansion in all directions of the explosive vapours from below. In some of the mud-cones already noticed, the crater is not more than a few inches in diameter and depth. From this minimum, every gradation of size may be met with, up to huge precipitous depressions, a mile or more in diameter, and several thousand feet in depth. In the crater of an active volcano, emitting lava and scoriæ, like Vesuvius, the walls are steep, rugged cliffs of scorched and blasted rock—red, yellow, and black. Where the material erupted is only loose dust and lapilli, the sides of the crater are slopes, somewhat steeper than those of the outside of the cone.

The crater-bottom of an active volcano of the first class, when quiescent, forms a rough plain dotted over with hillocks or cones, from many of which steam and hot vapours are ever rising. At night, the glowing lava may be seen lying in these vents, or in fissures, at a depth of only a few feet from the surface. Occasional intermittent eruptions take place and miniature cones of slag and scoriæ are thrown up. In some instances, as in the vast crater of Gurung Tengger, in Java, the crater-bottom stretches out into a wide level waste of volcanic sand, driven by the wind into dunes like those of the African deserts.

A volcano commonly possesses one chief crater, often also many minor ones, of varying or of nearly equal size. The volcano of the Isle of Bourbon (or Réunion) has three craters.[2] Not infrequently craters appear successively, owing to the blocking up of the pipe below. Thus in the accompanying plan of the volcanic cone of the island of Volcanello (Fig. 55), one of the Lipari group, the volcanic funnel has shifted its position twice, so that three craters have successively appeared upon the cone, and partially overlap each other. It may be from this cause that some volcanic mountains are now destitute of craters, or in other cases, because the lava has welled up in dome form covered perhaps with masses of scoriæ, but without the production of a definite crater. Mount Ararat, for example, is said to have no crater; but so late as the year 1840 a fissure opened on its side whence a considerable eruption took place. The trachytic puys of Auvergne are dome-shaped hills without craters.

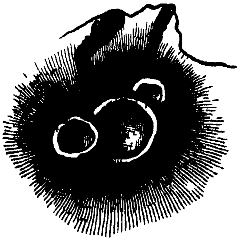

Fig. 55.—Plan of Volcanello, showing three successive craters.

Though the interior of modern volcanic cones can be at the best but very partially examined, the study of the sites of long-extinct cones, laid bare after denudation, shows that subsidence of the ground has commonly taken place at and round a vent. Evidence of subsidence has also been observed at some modern volcanoes (*ante*, p. 231). Theoretically two causes may be assigned for this structure. In the first place, the mere piling up of a huge mass of material round a given centre tends to press down the rock underneath, as some railway embankments may be observed to have done. This pressure must often amount to several hundred tons on the square foot. In the second place, the expulsion of volcanic material to the surface may leave cavities underneath, into which the overlying crust will naturally gravitate. These two causes combined, as suggested by Mr. Mallet, afford a probable explanation of the saucer-shaped depressions in which many ancient and some modern vents appear to lie.[1]

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[1] On the denudation of volcanic cones, see H. J. Johnston-Lavis, *Q. J. Geol. Soc.* xl. p. 103.

[2] For recent information regarding this volcanic island, see R. von Drasche, in *Verhandl. Geol. Reichsanst.* 1875, p. 266, and in Tschermak's *Min. Mittheil.* 1875 (3), p. 217 (4), p. 39, and his work 'Die Insel Réunion (Bourbon),' 4to, Vienna, 1878. C. Vélain, 'Description géologique de la Presqu'île d'Aden, de l'Ile de la Réunion, &c.,' Paris, 4to, 1878; and his work, 'Les Volcans,' 1884.

The following are the more important types of volcanic cones:[2]—

1. **Cones of Non-volcanic Materials.**—These are due to the discharge of steam or other aeriform product through the solid crust without the emission of any true ashes or lava. The materials ejected from the cavity are wholly, or almost wholly, parts of the surrounding rocks through which the volcanic pipe has been drilled. Some of the cones surrounding the crater lakes (*maare*) of the Eifel consist chiefly of fragments of the underlying Devonian slates (pp. 200, 213).

2. **Tuff-Cones, Cinder-Cones.**—Successive eruptions of fine dust and stones, often rendered pasty by mixture with the water so copiously condensed during an eruption, form a cone in which the materials are solidified by pressure into tuff. Cones made up only of loose cinders, like Monte Nuovo in the Bay of Baiæ, often arise on the flanks or round the roots of a great volcano, as happens to a small extent on Vesuvius, and on a larger scale upon Etna. They likewise occur by themselves apart from any lava-producing volcano, though usually they afford indications that columns of lava have risen in their funnels, and even now and then that this lava has reached the surface.

The cones of the Eifel district have long been celebrated for their wonderful perfection. Though small in size, they exhibit with singular clearness many of the leading features of volcanic structure. Those of Auvergne are likewise exceedingly instructive.[3] The high plateaux of Utah are dotted with hundreds of small volcanic cinder-cones, the singular positions of which, close to the edge of profound river-gorges and on the upthrow side of faults, have already (p. 204) been noticed. Among the Carboniferous volcanic rocks of central Scotland the stumps of ancient tuff-cones, frequently with a central core of basalt, or with dykes and veins of that rock, are of common occurrence.[1]

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[1] Mallet, *Q. J. Geol. Soc.* xxxiii. p. 740. See also the account of "Volcanic Necks," in Book IV. Part VII.

[2] Von Seebach (*Z. Deutsch. Geol. Ges.* xviii. 644) distinguished two volcanic types. 1st, *Bedded Volcanoes* (Strato-Vulkane), composed of successive sheets of lava and tuffs, and embracing the great majority of volcanoes. 2nd, *Dome Volcanoes*, forming hills composed of homogeneous protrusions of lava, with little or no accompanying fragmentary discharges, without craters or chimneys, or at least with only minor examples of these volcanic features. He believed that the same volcano might at different periods in its history belong to one or other of these types—the determining cause being the nature of the erupted lava, which, in the case of the dome volcanoes, is less fusible and more viscid than in that of the bedded volcanoes. (See below, under "Lava-cones.")

[3] For Auvergne, see works cited on p. 219. For the Eifel, consult Hibbert, 'History of the Extinct Volcanoes of the Basin of Neuwied on the Lower Rhine,' Edin. 1832. Von Dechen, 'Geognostischer Fuhrer zu dem Laacher See,' Bonn, 1864. 'Geognostischer Fuhrer in das Siebengebirge am Rhein,' Bonn, 1861.

The materials of a tuff-cone are arranged in more or less regularly stratified beds.

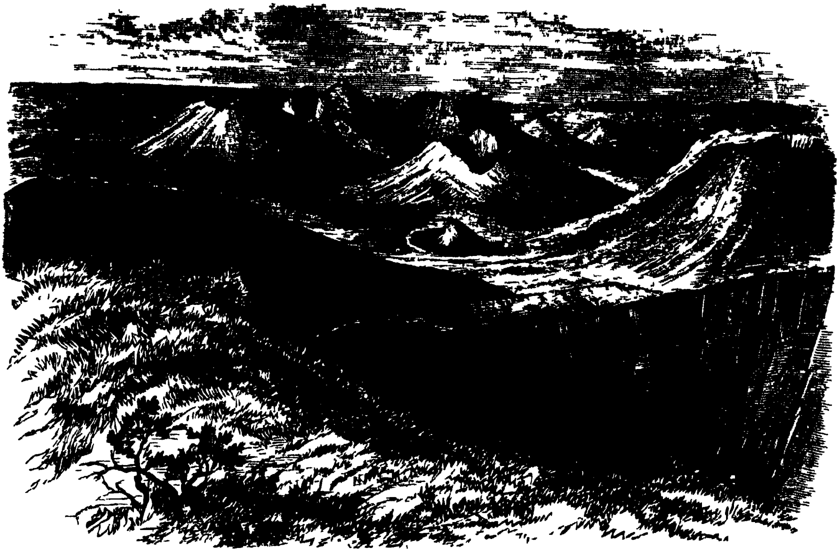

Fig 56.—View of the Tuff-cones of Auvergne, taken from the top of the cone and crater of Puy Pariou

On the outer side, they dip down the slopes of the cone at the average angle of repose, which may range between 30° and 40°. From the summit of the crater-lip they likewise dip inward toward the crater-bottom at similar angles of inclination (Fig. 57).

3. **Mud-Cones** resemble tuff-cones in form, but are usually smaller in size and less steep. They are produced by the hardening of successive outpourings of mud from the orifices already described (p. 238). In the region of the Lower Indus, where they are abundantly distributed over an area of 1000 square miles, some of them attain a height of 400 feet, with craters 30 yards across.[2]

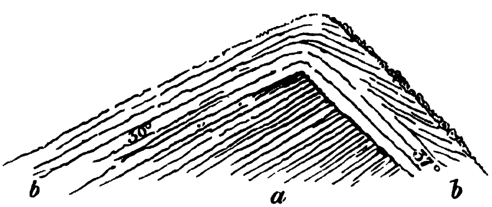

Fig 57.—Section of the crater-rim of the Island of Volcano
a, Older tuff; *b b*, younger ashes; the crater lies to the right

4. **Lava-cones.**—Volcanic cones composed entirely of lava are comparatively rare, but occur in some younger Tertiary and modern volcanoes. Fouqué describes the lava of 1866 at Santorin as having formed a dome-shaped elevation, flowing out quietly and

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[1] *Trans Roy. Soc. Edin.* xxix. p. 455. See *postea*, Book IV. Part VII.

[2] Lyell, 'Principles,' ii. p. 77.

rapidly without explosions. After several days, however, its emission was accompanied with copious discharges of fragmentary materials and the formation of several crateriform mouths on the top of the dome. Where lava possesses extreme liquidity, and gives rise to little or no fragmentary matter, it may build up a flat cone as in the remarkable examples described by Dana from the Hawaii Islands.[1] On the summit of Mauna Loa (Fig. 58), a flat lava-cone 13,760 feet above the sea, lies a crater, which in its deepest part is about 8000 feet broad, with vertical walls of stratified lava rising on one side to a height of 784 feet above the black lava-plain of the crater-bottom. From the edges of this elevated cauldron, the mountain slopes outward at an angle of not more than 6°, until, at a level of about 10,000 feet lower, its surface is indented by the vast pit-crater, Kilauea, about two miles long, and nearly a mile broad. So low are the surrounding slopes that these vast craters have been compared to open quarries on a hill or moor. The bottom of Kilauea is a lava-plain, dotted with lakes of extremely fluid lava in constant ebullition. The level of the lava has varied, for the walls surrounding the fiery flood consist of beds of similar lava, and are marked by ledges or platforms (Fig. 59) indicative of former successive heights of lava, as lake terraces show former levels of water. In the accompanying section (Fig. 60) the walls rising above the lower pit (*p p′*) were found to be 342 feet high, those bounding the higher terrace (*o n n o′*) were 650 feet high, all being composed of innumerable beds of lava, as in cliffs of stratified rocks. Much of the bottom of the lower lava-plain has been crusted over by the solidification of the molten rock. But large areas, which shift their position from time to time, remain in perpetual rapid ebullition. The glowing flood, as it boils up with a fluidity more like that of water than what is commonly shown by molten rock, surges against

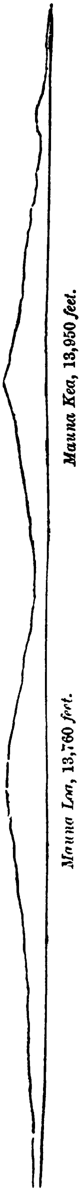

Fig. 58.—Profile of Lava-domes of Hawaii.

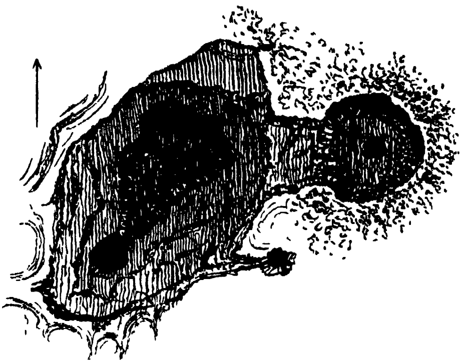

Fig. 59.—Plan of Lava-cauldron, Kilauea, Hawaii (Dana, 1841.[2])

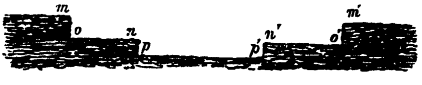

Fig. 60.—Section of Lava-terraces in Kilauea (Dana).

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[1] In Wilkes's *Report of U. S. Exploring Expedition*, 1838-42, and Dana's 'Characteristics of Volcanoes.' See the works cited on p. 205.

[2] For more recent maps showing the variations of this crater, see Dana's 'Characteristics.'

the surrounding terrace walls. Large segments of the cliffs undermined by the fusion of their base, fall at intervals into the fiery waves and are soon melted. Recent observations by Captain Dutton point to a diminution of the activity of this lava-crater. In Iceland, and in the Western Territories of North America, low domes of lava appear to mark the vents from which extensive basalt-floods have issued.

Where the lava assumes a more viscid character, as in trachyte and liparite, dome-shaped eminences may be protruded. As the mass increases in size by the advent of fresh material injected from below, the outer layer will be pushed outward, and successive shells will in like manner be enlarged as the eruption advances. On the cessation of discharges, we may conceive that a volcanic hill formed in this way will present an onion-like arrangement of its component sheets of rock. More or less perfect examples of this structure have been observed in Bohemia, Auvergne, and the Eifel[1] The trachytic domes of Auvergne form a conspicuous feature among the cinder cones of that region. Huge conical protuberances of granophyre occur among the Tertiary volcanic rocks of the Inner Hebrides, and similar hills of liparite rise through the basalts of Iceland.

5. **Cones of Tuff and Lava.**—This is by far the most abundant type of volcanic structure, and includes the great volcanoes of the globe. Beginning, perhaps, as mere tuff-cones, these eminences have gradually been built up by successive outpourings of lava from different sides, and by showers of dust and scoriæ. At first, the lava, if the sides of the cone are strong enough to resist its pressure, may rise until it overflows from the crater. Subsequently, as the funnel becomes choked up, and the cone is shattered by repeated explosions, the lava finds egress from different fissures and openings on the cone. As the mountain increases in height, the number of lava-currents from its summit will usually decrease. Indeed, the taller a volcanic cone grows, the less frequently as a rule does it erupt. The lofty volcanoes of the Andes have each seldom

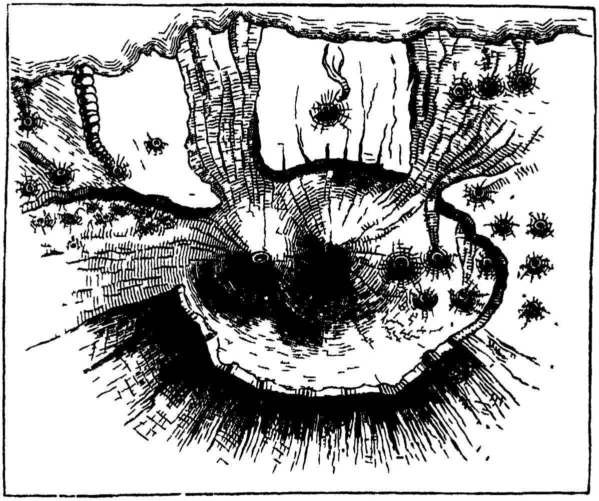
Fig. 61 —Plan of the Peak of Teneriffe, showing the large crater and minor cones.

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[1] E. Reyer (*Jahrb. Geol. Reichs.* 1879, p. 463) has experimentally imitated the process of extrusion by forcing up plaster of Paris through a hole in a board. For drawings of the Puy de Sarcouy and other dome-shaped hills which presumably have had this mode of origin, see Scrope's 'Geology and Extinct Volcanoes of Central France.' Refer also to the remarks already made on the liquidity of lava (*ante*, pp. 222-5), and the account of "Vulkanische Kuppen," *postea*, p. 255.

been more than once in eruption during a century. The peak of Teneriffe (Fig. 61) was three times active during 370 years prior to 1798.[1] The earlier efforts of a volcano tend to increase its height, as well as its breadth; the later eruptions chiefly augment the breadth, and are often apt to diminish the height by blowing away the upper part of the cone. The formation of fissures and the consequent intrusion of a network of lava-dykes, tend to bind the framework of the volcano and strengthen it against subsequent explosions. In this way, a kind of oscillation is established in the form of the cone, periods of crater-eruptions being succeeded by others when the emissions take place only laterally (*ante*, p. 210).

One consequence of lateral eruption is the formation of minor parasitic cones on the flanks of the parent volcano (p. 192). Those on Etna, more than 200 in number, are really miniature volcanoes, some of them reaching a height of 700 feet (Fig. 62). As the lateral vents successively become extinct, the cones are buried under sheets of lava and showers of débris thrown out from younger openings or from the parent cone. It sometimes happens that the original funnel is disused, and that the eruptions of the volcano

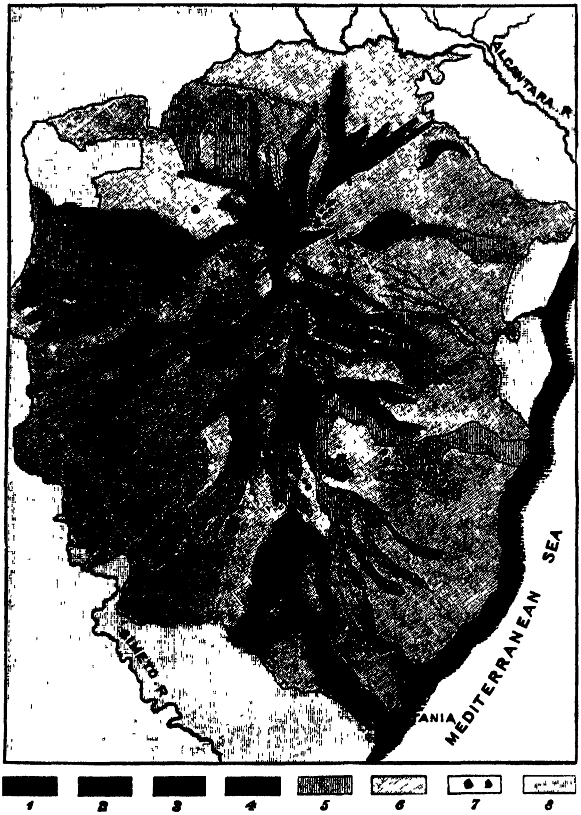

Fig. 62.—Map of Etna, after Sartorius von Waltershausen.
1, Lava of 1879; 2, Lavas of 1865 and 1852; 3, Lava of 1669; 4, Recent Lavas; 5, Lavas of the Middle Ages; 6, Ancient Lavas of unknown date; 7, Cones and Craters; 8, Non-volcanic Rocks.

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[1] For a recent account of Teneriffe, see A. Rothpletz, *Petermann's Mittheil.* xxxv. (1889), p. 237.

take place from a newer main vent. Vesuvius, for example (as shown in Figs. 63 and 45), stands on the site of a portion of the rim of the more ancient and much larger vent of Monte Somma. The present crater of Etna lies to the north-west of the former vaster crater. The pretty little example of this shifting furnished by Volcanello has been already noticed (p. 243).

While, therefore, a volcano, and more particularly one of great size, throwing out both lava and fragmentary materials, is liable to continual modification of its external form, as the result of successive eruptions, its contour is likewise usually exposed to extensive alteration by the effects of ordinary atmospheric erosion, as well as from the condensation of the volcanic vapours. Heavy and sudden floods, produced by the rapid rainfall consequent upon a copious discharge of steam, rush down the slopes with such volume and force as to cut deep gullies in the loose or only partially consolidated tuffs and scoriæ. Ordinary rain continues the erosion until the outer slopes, unless occasionally renewed by fresh showers of detritus, assume a curiously furrowed aspect, like a half-opened umbrella, the ridges being separated by furrows that narrow upwards towards the summit of the cone. The outer declivities of Monte Somma afford an excellent illustration of this form of surface, the numerous ravines on that side of the mountain presenting instructive sections of the pre-historic lavas and tuffs of the earlier and more important period in the history of this volcano.[1] Similar trenches have been eroded on the southern or Vesuvian side of the original cone, but these have in great measure been filled up by the lavas of the younger mountain. The ravines, in fact, form natural channels for the lava, as may unfortunately be seen round the Vesuvian observatory. This building is placed on one of the ridges between two deep ravines; but the lava-streams of recent years have poured into these ravines on either side, and are rapidly filling them up.

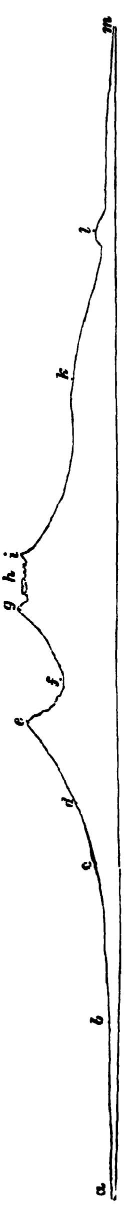

Fig. 63.—Section of Vesuvius and Monte Somma from north to south.

a, Plain of the Campagna; *b*, Village of Somma (413 French feet); *c*, Fontana dell' Olivella (994); *d*, Casa Cancaroni (1588); *e*, Punta di Nasone (3430), on crest of old crater of Monte Somma; *f*, Atrio del Cavallo, bottom of old Crater of Monte Somma; *g*, *i*, edges of modern crater (*h*) of Vesuvius (3640); *k*, Boche Nuove (1515); *l*, Camaldoli (534); *m*, Torre dell' Annunziata, on Bay of Naples.

Submarine Volcanoes.—It is not only on the surface of the land that volcanic action shows itself. It takes place likewise under the sea, and as the geological records of the earth's past history are chiefly marine formations, the characteristics of submarine volcanic action have no small interest for the geologist. In a few instances, the actual outbreak of a submarine eruption has been witnessed. Thus, in the early summer of 1783, a volcanic eruption took place about thirty miles from Cape Reykjanaes on the west coast of Iceland. An island was built up, from which fire and smoke continued to issue, but in less than a year the waves had washed the loose pumice away, leaving a submerged reef from five to thirty fathoms below sea-level. About a month after this eruption, the frightful outbreak of Skaptar Jökull, already referred to (p. 222), began, the distance of this mountain from the submarine vent being nearly 200 miles.[1] A century afterwards, viz. in July 1884, another volcanic island is said to have been thrown up near the same spot, having at first the form of a flattened cone, but soon yielding to the power of the breakers. Many submarine eruptions have taken place within historic times in the Mediterranean. The most noted of these occurred in the year 1831, when a new volcanic island (Graham's Island, Ile Julia) was thrown up, with abundant discharge of steam and showers of scoriæ, between Sicily and the coast of Africa. It reached an extreme height of 200 feet or more above the sea-level (800 feet above sea-bottom) with a circumference of 3 miles, but on the cessation of the eruptions, was attacked by the waves and soon demolished, leaving only a shoal to mark its site.[2] In the year 1811, another island was formed by submarine eruption of the coast off St. Michael's in the Azores (Fig. 64). Consisting, like the Mediterranean example, of loose cinders, it rose to a height of about 300 feet, with a circumference of about a mile, but subsequently disappeared.[3] In the year 1796 the island of Johanna Bogoslawa, in Alaska, appeared above the water, and in four years had grown into a large volcanic cone, the summit of which was 3000 feet above sea-level.[4]

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[1] See H. J. Johnston-Lavis, *Q. J. Geol. Soc.* xl. p. 103.

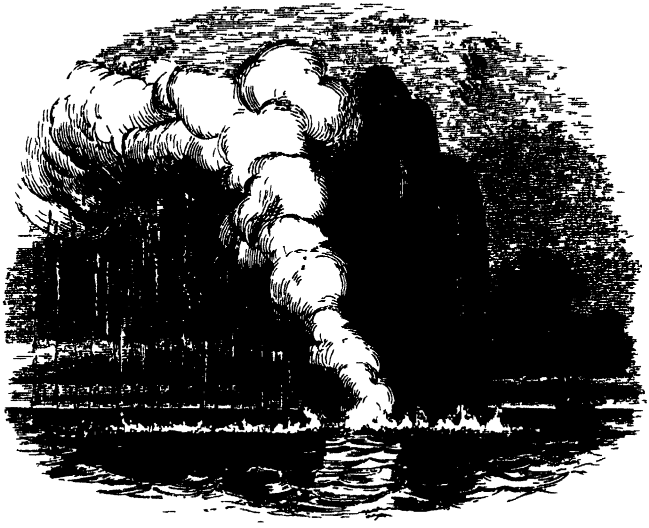

Fig. 64.—Sketch of submarine volcanic eruption (Sabrina Island) off St. Michael's, June 1811.

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[1] Lyell, 'Principles,' ii. p. 49.

[2] *Phil. Trans.* 1832. Constant Prévost, *Ann. des Sci. Nat.* xxiv. *Mém. Soc. Géol. France*, ii. p. 91. Mercalli's 'Vulcani, &c.,' p. 117. For a recent submarine eruption in the Mediterranean, see Ricco, *Compt. rend.* Nov. 23rd, 1891.

[3] De la Beche, 'Geological Observer,' p. 70.

[4] D. Forbes, *Geol. Mag.* vii. p. 323.

Unfortunately, the phenomena of recent volcanic eruptions under the sea are for the most part inaccessible. Here and there, as in the Bay of Naples, at Etna, among the islands of the Greek Archipelago, and at Tahiti, elevation of the sea-bed has taken place, and brought to the surface beds of tuff or of lava which have consolidated under water. Both Vesuvius and Etna began their career as submarine volcanoes.[1] It will be seen from the accompanying chart (Fig. 65), that the Islands of Santorin and Therasia form the unsubmerged portions of a great crater-rim rising round a crater which descends 1278 feet below sea-level. The materials of these islands consist of a nucleus of marbles and schists, nearly buried under a pile of tuffs (trass), scoriæ, and sheets of lava, the bedded character of which is well shown in the accompanying sketch

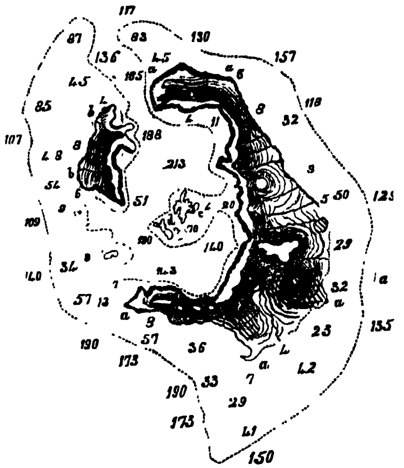

Fig. 65.—Map of partially-submerged volcano of Santorin.

a, Thera, or Santorin; *b*, Therasia; *c*, Mikro Kaimeni; *d*, Neo Kaimeni. The figures denote soundings in fathoms, the dotted line marks the 100 fathoms line.

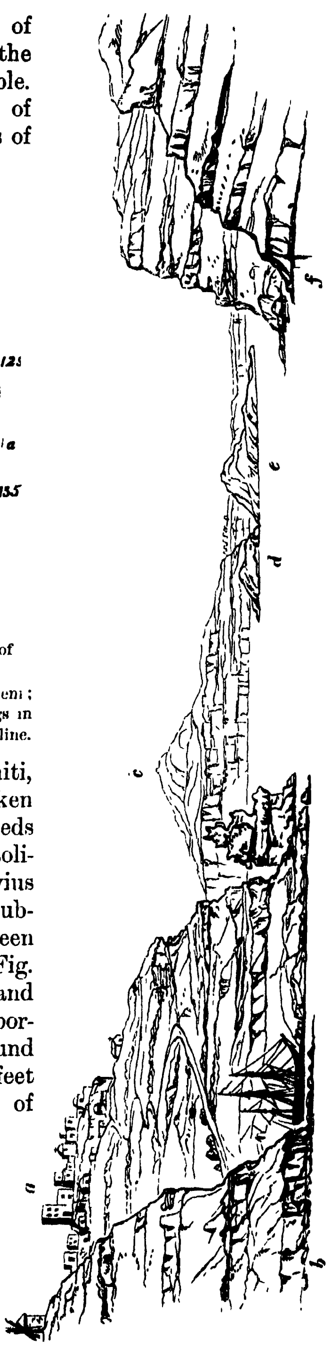

Fig. 66.—View of the interior of the crater of Santorin from the entrance.

a, Town of Apanomeria, standing on tuffs, &c.; *b*, North-west cape of Santorin, with bedded tuffs and lavas; *c*, Mount St. Elias (568 mètres), consisting of marble, &c. (shown by oblique lines in the chart, Fig. 65) and forming with the surrounding district a non-volcanic tract in the midst of the lavas and tuffs; *d*, Mikro Kaimeni; *e*, Neo Kaimeni, the scene of the eruptions in 1866-67; *f*, Therasia, an island composed, like Santorin, of beds of tuff, slags, and lavas.

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[1] See, as regards Etna, 'Der Aetna,' ii. p. 327.

by Admiral Spratt (Fig. 66), who, with the late Professor Edward Forbes, examined the geology of this interesting district in 1841. They found some of the tuffs to contain marine shells, and thus to bear witness to an elevation of the sea-floor since volcanic action began. More recently the islands have been carefully studied by various observers. K. von Fritsch has found recent marine shells in many places up to heights of nearly 600 feet above the sea. The strata containing these remains he estimates to be at least 100 to 120 mètres thick, and he remarks that in every case he found them to consist essentially of volcanic débris and to rest upon volcanic rocks. It is evident, therefore, that these shell-bearing tuffs were originally deposited on the sea-floor after volcanic action had begun here, and that during later times they were upraised, together with the submarine lavas associated with them.[1] Fouqué concludes that the volcano formed at one time a large island with wooded slopes and a somewhat civilised human population, cultivating a fertile valley in the south-western district, and that in prehistoric times the tremendous explosion occurred whereby the centre of the island was blown out.

The similarity of the structure of Santorin to that of Somma and Etna is obvious. Volcanic action still continues there, though on a diminished scale. In 1866-67 an eruption took place on Neo Kaimeni, one of the later-formed islets in the centre of the old crater, and greatly added to its area and height. The recent eruptions of Santorin, which have been studied in great detail, are specially interesting from the additional information they have supplied as to the nature of volcanic vapours and gases. Among these, as already stated (p. 196), free hydrogen plays an important part, constituting, at the focus of discharge, thirty per cent of the whole. By their eruption under water, the mingling of these gases with atmospheric air and the combustion of the inflammable compounds is there prevented, so that the gaseous discharges can be collected and analysed. Probably were operations of this kind more practicable at terrestrial volcanoes, free hydrogen and its compounds would be more abundantly detected than has hitherto been possible.

The numerous volcanoes which dot the Pacific Ocean, probably in most cases began their career as submarine vents, their eventual appearance as subaerial cones being mainly due to the accumulation of erupted material, but also partially, as in the case of Santorin, to actual upheaval of the sea-bottom. The lonely island of St. Paul (Figs. 67 and 69), lying in the Indian Ocean more than 2000 miles from the nearest land, is a notable example of the summit of a volcanic mountain rising to the sea-level in mid-ocean. Its circular crater, broken down on the north-east side, is filled with water, having a depth of 30 fathoms.[1]

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[1] See Fritsch, *Z. Deutsch. Geol. Ges.* xxiii. (1871), pp. 125-213. The most complete and elaborate work is Fouqué's monograph (already cited), 'Santorin et ses Eruptions,' Paris, 4to, 1880, where copious analyses of rocks, minerals, and gaseous emanations, with maps and numerous admirable views and sections, are given. In this volume a bibliography of the locality will be found. Compare C. Doelter on the Ponza Islands, *Denksch. Akad. Wissensch.* Vienna, xxxvi. p. 141. *Sitz. Akad. Wissensch.* Vienna, lxxi. (1875), p. 49.

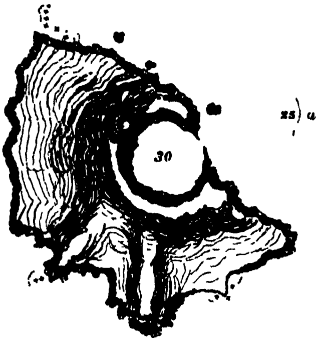

Fig. 67.—Volcanic crater of St. Paul Island, Indian Ocean.

Observations by R. von Drasche have shown that at Bourbon (Réunion), during the early submarine eruptions of that volcano, coarsely crystalline rocks (gabbro) were emitted, that these were succeeded by andesitic and trachytic lavas: but that when the vent rose above the sea, basalts were poured out.[2] Fouqué observes that at Santorin some of the early submarine lavas are identical with those of later subaerial origin, but that the greater part of them belong to an entirely different series, being acid rocks, belonging to the group of hornblende-andesites, while the subaerial rocks are augite-andesites. The acidity of these lavas has been largely increased by the infusion into them of much silica, chiefly in the form of opal. They differ much in aspect, being sometimes compact, scoriaceous, hard, like millstone, with perlitic and spherulitic structures, while they frequently present the characters of trass impregnated with opal and zeolites. Among the fragmental ejections there occur blocks of schist and granitoid rocks, probably representing the materials below the sea-floor through which the first explosion took place (pp. 200, 213, 244). During the eruption of 1866 some islets of lava rose above the sea in the middle of the bay, near the active vent. The rock in these cases was compact, vitreous, and much cracked.[3]

Among submarine volcanic formations, the tuffs differ from those laid down on land chiefly in their organic contents; but partly also in their more distinct and originally less inclined bedding, and in their tendency to the admixture of non-volcanic or ordinary mechanical sediment with the volcanic dust and stones. No appreciable difference either in external aspect or in internal structure seems yet to have been established between subaerial and submarine lavas. Some undoubtedly submarine lavas are highly scoriaceous. There is no reason, indeed, why slaggy lava and loose, non-buoyant scoriæ should not accumulate under the pressure of a deep column of the ocean. At the Hawaii Islands, on 25th February 1877, masses of pumice, during a submarine volcanic explosion, were ejected to the surface, one of which struck the bottom of a boat with considerable violence and then floated. When we reflect, indeed, to what a considerable extent the bottom of the great ocean-basins is dotted over with volcanic cones, rising often solitary from profound depths, we can believe that a large proportion of the actual eruptions in oceanic areas may take place under the sea. The immense abundance and wide diffusion of volcanic detritus (including blocks of pumice) over the bottom of the Pacific and Atlantic oceans, even at distances remote from land, as made known by the voyage of the *Challenger*, doubtless indicate the prevalence and persistence of submarine volcanic action, even though, at the same time, an extensive diffusion of volcanic débris from the islands is admitted to be effected by winds and ocean currents.

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[1] For a general account of the volcanic islands of the ocean, see Darwin's 'Volcanic Islands,' 2nd edit. 1876. For the Philippine volcanoes, see R. von Drasche, *Tschermak's Mineralogische Mittheil.* 1876; Semper's 'Die Philippinen und ihre Bewohner,' Wurzburg, 1869. For the Kurile Islands, J. Milne, *Geol. Mag.* 1879, 1880, 1881; Volcanoes of Bay of Bengal (Barren Island, &c.), V. Ball, *Geol. Mag.* 1879, p. 16; 1888, p. 404; F. R. Mallet, *Mem. Geol. Surv. India*, xxi. part iv. St. Paul (Indian Ocean), C. Vélain, *Assoc. Fran.* 1875, p. 581; 'Mission à l'île St. Paul,' 1879; 'Description géologique de la Presqu'île d'Aden,' &c., 4to, Paris, 1878; and 'Les Volcans,' 1884. For Isle of Bourbon, see authorities cited on p. 243, and for Hawaii, the references on p. 205.

[2] Tschermak's *Mineralogische Mittheil.* 1876, pp. 42, 157. A similar structure occurs at Palma (Cohen, *Neues Jahrb.* 1879, p. 482) and in St. Paul (Vélain as above cited).

[3] Fouqué, 'Santorin.'

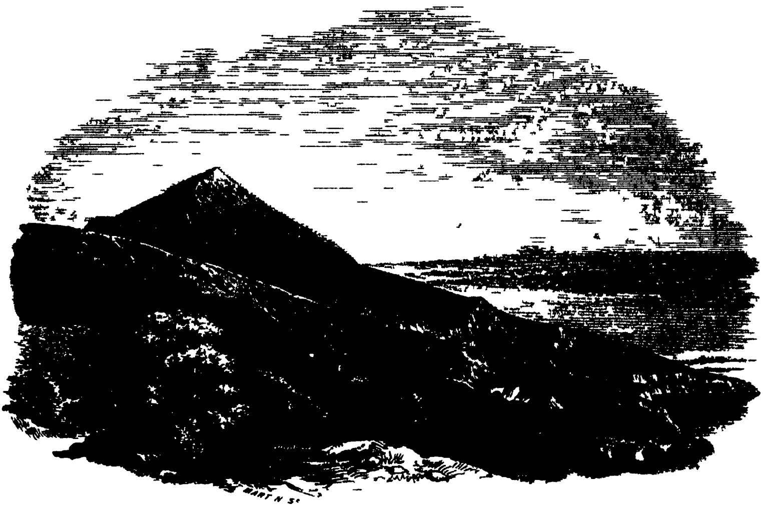

Fig 68 View of the Peak of Teneriffe and its coast erosion

Volcanic islands, unless continually augmented by renewed eruptions, are attacked by the waves and cut down. Graham's Island and the other examples above cited show how rapid this disappearance may

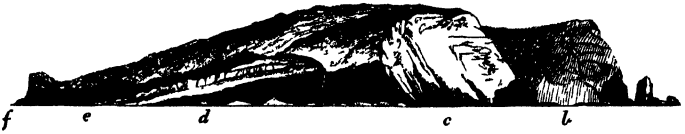

Fig. 69 —View of St Paul Island, Indian Ocean, from the east (Capt Blackwood in Admiralty Chart) *a*, Nine-pin Rock, a stack of harder rock left by the sea, *b*, entrance to crater lagoon (see Fig 67), *c*, *d*, *e*, cliffs composed of bedded volcanic materials dipping towards the south, and much eroded at the higher end (*c*) by waves and subaerial waste, *f*, southern point of the island, likewise cut away into a cliff

be. The island of Volcano has the base of its slopes truncated by a line of cliff due to marine erosion. The island of Teneriffe shows, in the same way, that the sea is cutting back the land towards the great cone (Fig. 68). The island of St. Paul (Figs. 67, 69) brings before us in a more impressive way the tendency of volcanic islands to be destroyed unless replenished by continual additions to their surface. At St. Helena lofty cliffs of volcanic rocks 1000 to 2000 feet high bear witness to the enormous denudation whereby masses of basalt two or three miles long, one or two miles broad, and 1000 to 2000 feet thick, have been entirely removed.[1]

ii. *Fissure (Massive) Eruptions.*

Under the head of massive or homogeneous volcanoes some geologists have included a great number of bosses or dome-like projections of once-melted rock which, in regions of extinct volcanoes, rise conspicuously above the surface without any visible trace of cones or craters of fragmentary material. They are usually regarded as protrusions of lava, which, like the Puy de Dôme in Auvergne, assumed a dome-form at the surface without spreading out in sheets over the surrounding country, and with no accompanying fragmentary discharges. But the mere absence of ashes and scoriæ is no proof that these did not once exist, or that the present knob or boss of lava may not originally have solidified within a cone of tuff which has been subsequently removed in denudation. The extent to which the surface of the ground has been changed by ordinary atmospheric waste, and the comparative ease with which loose volcanic dust and cinders might have been entirely removed, require to be considered. Hence, though the ordinary explanation is no doubt in some cases correct, it may be doubted whether a large proportion of the examples cited from the Rhine, Bohemia, Hungary, and other regions, ought not rather to be regarded like the "necks" so abundant in the ancient volcanic districts of Britain (Book IV. Part VII.) as the remaining roots of ordinary volcanic cones. If the tuff of a cone, up the funnel of which lava rose and solidified, were swept away, we should find a central lava plug or core resembling the volcanic "heads" (*vulkanische Kuppen*) of Germany. Unquestionably, lava has in innumerable instances risen in this way within cones of tuff or cinders, partially filling them without flowing out into the surrounding country.[2]

But while, on either explanation of their origin, these volcanic "heads" find their analogues in the emissions of lava in modern volcanoes, there are numerous cases in old volcanic areas where the eruptions, so far as can now be judged, were not attended with the production of any central cone or crater. Such emissions of lava may have resembled those which in recent times have occurred at the Hawaiian volcanoes, where enormous accumulations of lava have gradually been built up into flat domes, of which Mauna Loa rises to a height of 13,675 feet. Vast floods of remarkably liquid basic lava have from time to time flowed out tranquilly without explosion or earthquake, and with no accompaniment of fragmental discharges. These currents of molten rock have spread out into wide sheets, sloping at so low an angle that they look horizontal. The lower and older portions of them have been eroded by streams so as to present escarpments and outliers not unlike those of western North America or the older basaltic plateaux of Britain and India.[1]

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[1] Darwin, 'Volcanic Islands,' p. 104. For a more detailed account of this island, see J. C. Melliss' 'St. Helena,' London, 1875.

[2] Von Seebach, *Z. Deutsch. Geol. Ges.* xviii. p. 643. F. von Hochstetter, *Neues Jahrb.* 1871, p. 469. Reyer, *Jahrb. K. K. Geol. Reichsanstalt*, 1878, p. 81; 1879, p. 463.

The most stupendous modern basaltic-floods of Iceland issued from vents along a fissure. According to Thoroddsen the post-glacial lava-fields of Odadahraun, covering an area of about 4390 square kilometres, have issued from about 20 distinct vents, while in the east of Iceland the lava has flowed from the lips of fissures.[2] It would seem that for the discharge of such wide and flat sheets of lava, great mobility and tolerably complete fusion of the molten mass is necessary. The phenomenon occurs among the more basic lavas (basalts, &c.) rather than among the more lithoid acid lavas (trachytes, rhyolites, &c.)

In former geological ages, extensive eruptions of lava, without the accompaniment of scoriæ, with hardly any fragmentary materials, and with, at the most, only flat dome-shaped cones at the points of emission, have taken place over wide areas from scattered vents, along lines or systems of fissures. Vast sheets of lava have in this manner been poured out to a depth of many hundred feet, completely burying the previous surface of the land and forming wide plains or plateaux. These truly "massive eruptions" have been held by Richthofen[3] and others to represent the grand fundamental character of volcanism, ordinary volcanic cones being regarded merely as parasitic excrescences on the subterranean lava-reservoirs, very much in the relation of minor cinder cones to their parent volcano.[4]

Though a description of these old fissure or massive eruptions ought properly to be included in Book IV., the subject is so closely connected with the dynamics of existing active volcanoes that an account of the subject may be given here. Perhaps the most stupendous example of this type of volcanic structure occurs in Western North America. The extent of country which has been flooded with basalt in Oregon, Washington, California, Idaho, and Montana has not yet been accurately surveyed, but has been estimated to cover a larger area than France and Great Britain combined, with a thickness averaging 2000 but reaching in some places to 3700 feet.[5] The Snake River plain in Idaho (Fig. 70) forms part of this lava-flood. Surrounded on the north and east by lofty mountains, it stretches westward as an apparently boundless desert of sand and bare sheets of black basalt. A few streams descending into the plain from the hills are soon swallowed up and lost. The Snake River, however, flows across it, and has cut out of its lava-beds a series of picturesque gorges and rapids. Looked at from any point on its surface, it appears as a vast level plain like that of a lake-bottom, though more detailed examination may detect a slope in one or more directions, and may thereby obtain evidence as to the sites of the chief openings from which the basalt was poured forth. The uniformity of surface has been produced either by the lava flowing over a plain or lake-bottom, or by the complete effacement of an original and undulating contour of the ground under hundreds of feet of volcanic rock in successive sheets. The lava rolling up to the base of the mountains has followed the sinuosities of their margin, as the waters of a lake follow its promontories and bays. The author crossed the Snake River plain in 1879, and likewise rode for many miles along its northern edge. He found the surface to be everywhere marked with low hummocks or ridges of bare black basalt, the surfaces of which exhibited a reticulated pavement of the ends of columns. In some places, there was a perceptible tendency in these ridges to range themselves in one general north-easterly direction, when they might be likened to a series of long, low waves, or ground-swells. In many instances the crest of each ridge had cracked open into a fissure which presented along its walls a series of tolerably symmetrical columns (Fig. 70). That these ridges were original undulations of the lava, and had not been produced by erosion, was indicated by the fact that the columns were perpendicular to their surface, and changed in direction according to the form of the ground which was the original cooling surface of the lava Though the

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[1] For a graphic account of the Hawaiian lava-fields, see Captain Dutton, Fourth Annual Report, U. S. Geol. Survey for 1882-83. See also Dana's 'Characteristics of Volcanoes.'

[2] See W. L. Watts' "Across the Vatna Jokull," *Proc. Roy. Geog. Soc.* 1876. W. G. Lock, *Geol. Mag.* 1881, p. 212; and papers by Thoroddsen and Helland, quoted *ante*, p. 202.

[3] *Trans. Akad. Sci. California*, 1868.

[4] *Proc. Roy. Phys. Soc. Edin.* v. 236; *Nature*, xxiii. p. 3.

[5] J. LeConte. *Amer. Journ. Sci.* 3rd ser. vii. (1874), 167, 259.

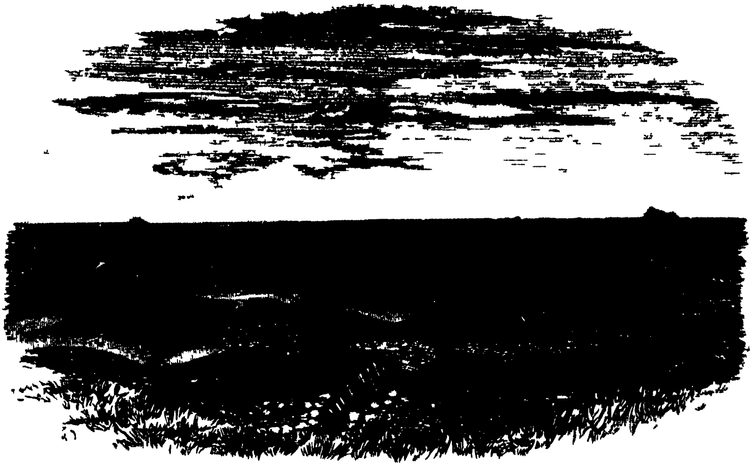

Fig 70 —View of the great Basalt plain of the Snake River, Idaho, with recent cones

basalt was sometimes vesicular, no layers of slag or scoriæ were anywhere observed, nor did the surfaces of the ridges exhibit any specially scoriform character.

There are no great cones whence this enormous flood of basalt could have flowed. It probably escaped from orifices or fissures still concealed under the sheets which issued from them, the points of escape being marked only by such low domes as could readily be buried under the succeeding eruptions from other vents.[1] That it was not the result of one sudden outpouring of rock is shown by the distinct bedding of the basalt, which is well marked along the river ravines. It arose from what may have been, on the whole, a continuous though locally intermittent welling-out of lava, probably from vents on many fissures extending over a wide tract of Western America during a late Tertiary period, if, indeed, the eruptions did not partly come within the time of the human occupation of the continent. The discharge of lava continued until the previous topography was buried under some 2000 feet of lava, only the higher summits still projecting above the volcanic flood.[2] At a few points on the plain and on its northern margin, the author observed some small cinder cones (Fig. 70). These were evidently formed during the closing stages of volcanic action, and may be compared to the minor cones on a modern volcano, or better, to those on the surface of a recent lava-stream.

In Europe, during older Tertiary time, similar enormous outpourings of basalt covered many hundreds of square miles. The most important of these is that which occupies a large part of the north-east of Ireland, and in disconnected areas extends through the Inner Hebrides and the Faröe Islands into Iceland. Throughout that region, the paucity of evidence of volcanic vents is truly remarkable. So extensive has been the denudation, that the inner structure of the volcanic plateaux has been admirably revealed. The ground beneath and around the basalt-sheets has been rent into innumerable fissures which have been filled by the rise of basalt into them. A vast number of basalt-dykes ranges from the volcanic area eastwards across Scotland and the north of England and the north of Ireland. Towards the west the molten rock reached the surface and was poured out there, while to the eastward it does not appear to have overflowed, or, at least, all evidence of the outflow has been removed in denudation. When we reflect that this system of dykes can be traced from the Orkney Islands southwards into Yorkshire and across Britain from sea to sea, over a total area of probably not less than 100,000 square miles, we can in some measure appreciate the volume of molten basalt which in older Tertiary times underlay large tracts of the site of the British Islands, rose up in so many thousands of fissures, and poured forth at the surface over so wide an area in the north-west.[3]

In Africa, basaltic plateaux cover large tracts of Abyssinia, where by the denuding effect of heavy rains they have been carved into picturesque hills, valleys, and ravines.[1] In India, an area of at least 200,000 square miles is covered by the singularly horizontal volcanic plateaux of the "Deccan Traps" (lavas and tuffs), which belong to the Cretaceous period and attain a thickness of 6000 feet or more.[2] The underlying platform of older rock, where it emerges from beneath the edges of the basalt tableland, is found to be in many places traversed by dykes; but no cones and craters are anywhere visible. In these, and probably in many other examples still undescribed, the formation of great plains or plateaux of level sheets of lava is to be explained by "fissure-eruptions" rather than by the operations of volcanoes of the familiar "cone and crater" type.

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[1] Captain Dutton has remarked the absence of any conspicuous feature at the sources from which some of the largest lava-streams of Hawaii have issued.

[2] Professor J. LeConte believes that the chief fissures opened in the Cascade and Blue Mountain Ranges. *Amer. Journ. Sci.* 3rd series, vii. (1874), p. 168.

[3] *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 21.

§ 4. Geographical and geological distribution of volcanoes.

Adequately to trace the distribution of volcanic action over the globe, account ought to be taken of dormant and extinct volcanoes, likewise of the proofs of volcanic outbreaks during earlier geological periods. When this is done, we learn, on the one hand, that innumerable districts have been the scene of prolonged volcanic activity, where there is now no underground commotion, and on the other, that volcanic outbursts have been apt to take place again and again after wide intervals on the same ground, some modern active volcanoes being thus the descendants and representatives of older ones. Some of the facts regarding former volcanic action have been already stated. Others will be given in Book IV. Part VII.

Confining attention to vents now active, of which the total number may be about 300,[3] the chief facts regarding their distribution over the globe may be thus summarised. (1) Volcanoes occur along the margins of the ocean-basins, particularly along lines of dominant mountain-ranges, which either form part of the mainland of the continents or extend as adjacent lines of islands. The vast hollow of the Pacific is girdled with a wide ring of volcanic foci. (2) Volcanoes rise, as a striking feature, from the submarine ridges that traverse the ocean basins. All the oceanic islands are either volcanic or formed of coral, and the scattered coral-islands have in all likelihood been built upon the tops of submarine volcanic cones. (3) Volcanoes are situated not far from the sea. The only exceptions to this rule are certain vents in Mantchouria and in the tract lying between Thibet and Siberia; but of the actual nature of these vents very little is yet known. (4) The dominant arrangement of volcanoes is in series along subterranean lines of weakness, as in the chain of the Andes, the Aleutian Islands, and the Malay Archipelago. A remarkable zone of volcanic vents girdles the globe from Central America eastward by the Azores and Canary Islands to the Mediterranean, thence to the Red Sea, and through the chains of islands from the south of Asia to New Zealand and the heart of the Pacific. (5) On a smaller scale the linear arrangement gives place to one in groups, as in Italy, Iceland, and the volcanic islands of the great oceans.

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[1] Blanford's 'Abyssinia,' 1870, p. 181.

[2] Medlicott and Blanford, 'Geology of India,' p. 299.

[3] This number is probably below the truth. Prof. J. Milne has enumerated in Japan alone no fewer than fifty-three volcanoes which are either active or have been active within a recent period. He remarks that, "if we were in a position to indicate the volcanoes which had been in eruption during the last 4000 years, the probability is that they would number several thousands rather than four or five hundred." 'Earthquakes and other Earth-movements,' 1886, p. 227. Compare Fisher, 'Physics of Earth's Crust,' 2nd ed. chap. xxiv.

In the European area there are six active volcanoes—Vesuvius, Etna, Stromboli, Volcano, Santorin, and Nisyros. Asia contains twenty-four, Africa ten, North America twenty,[1] Central America twenty-five, and South America thirty-seven.[2] By much the largest number, however, occur on islands in the ocean. In the Arctic Ocean rises the solitary Jan Mayen. On the ridge separating the Arctic and Atlantic basins, the group of Icelandic volcanoes is found. Along the great central ridge of the Atlantic bottom, numerous volcanic vents have risen above the surface of the sea—the Azores, Canary Islands, and the extinct degraded volcanoes of St. Helena, Ascension and Tristan d'Acunha. On the eastern border lie the volcanic vents of the islands off the African coast, and to the west those of the West India Islands. Still more remarkable is the development of volcanic energy in the Pacific area. From the Aleutian Islands southwards, a long line of volcanoes, numbering upwards of a hundred active vents, extends through Kamtschatka and the Kurile Islands to Japan,[3] whence another numerous series carries the volcanic band far south towards the Malay Archipelago, which must be regarded as the chief centre of the present volcanic activity of our planet. In Sumatra, Java, and adjoining islands, no fewer than fifty active vents occur. The chain is continued through New Guinea and the groups of islands to New Zealand.[4] Even in the Antarctic regions, Mounts Erebus and Terror are cited as active vents; while in the centre of the Pacific Ocean rise the great lava cones of the Sandwich Islands. In the Indian Ocean, the Red Sea, and off the east coast of Africa a few scattered vents appear.

Besides the existence of extinct volcanoes which have obviously been active in comparatively recent times, the geologist can adduce proofs of the former presence of active volcanoes in many countries where cones, craters, and all the ordinary aspects of volcanic mountains, have long disappeared, but where sheets of lava, beds of tuff, dykes, and necks representing the sites of volcanic vents have been recognised abundantly (Book IV. Part VII.) These manifestations of volcanic action, moreover, have as wide a range in geological time as they have in geographical area. Every great geological period, back into pre-Cambrian time, seems to have had its volcanoes. In Britain, for instance, there were probably active volcanic vents in pre-Cambrian ages. The Archæan gneiss of N.-W. Scotland includes a remarkable series of dykes presenting some points of resemblance to the great Tertiary system. The Torridon sandstone of the same region, which is now known to be pre-Cambrian, contains pebbles of various finely vesicular porphyrites, and in one place includes a band of true tuff. In the lower Cambrian period the tuffs and diabases of Pembrokeshire were erupted. Still more vigorous were the volcanoes in the Lower Silurian period, when the lavas and tuffs of Snowdon, Aran Mowddwy, and Cader Idris were ejected. During the deposition of the Upper Silurian rocks a few volcanoes were active in the west of Ireland. The Lower Old Red Sandstone epoch was one of prolonged activity in central Scotland. The earlier half of the Carboniferous period likewise witnessed two distinct epochs of volcanic activity over the same region. In the earlier of those, lavas (andesites and trachytes) were poured out in wide level plateaux from many vents, while in the later, groups of minor cones like the puys of Auvergne were dispersed among the lagoons. During Permian time, more than a hundred small vents rose in scattered groups across the centre and south-west of Scotland, while a few similar points of eruption appeared in the south-west of England. No trace of any British Mesozoic volcanoes has been met with. The vast interval between Permian and older Tertiary time appears to have been a period of total quiescence of volcanic activity. The older Tertiary ages were distinguished by the outpouring of the enormous basaltic plateaux of Antrim and the Inner Hebrides.[1]

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[1] For an account of the remarkable extinct volcanoes of Northern California, Oregon, and Washington Territory, see A. Hague and J. P. Iddings. *Amer. Journ. Sci.* xxvi. (1883), p. 222. On Volcanoes of Mexico see H. Lenk, 'Beitrage zur Geologie und Palæontologie der Repbulik Mexico,' Leipzig, 1890; of Central America, A. Dolfuss and E. de Monserrat, 'Voyage Géologique,' Paris, folio, 1868; K. von Seebach, *Abh. Kön. Ges. Wiss. Göttingen*, xxxviii. (1892).

[2] For a recent account of the volcanoes of the Andes of the Equator see Whymper's 'Travels Amongst the Great Andes.'

[3] For the volcanoes of Japan, besides papers quoted on p. 213, see W. J. Holland, *Appalachia*, vi. (1890), 109. E. Naumann, *Zeitsch. Deutsch. Geol. Ges.* 1877, p. 364. Mr. Milne enumerates 100 active vents from the Kuriles to Kiushu (2000 miles).

[4] The great eruption of Tarawera, New Zealand, in 1886, is described by Prof. A. P. W. Thomas, 'Report on the Eruption of Tarawera,' published by the Government in 1888: also Prof. Hutton's 'Report on the Tarawera Volcanic District, Wellington, 1887,' *Quart. Journ. Geol. Soc.* xliii. (1887), p. 178.

In France and Germany, likewise, Palæozoic time was marked by the eruption of many diabase, porphyrite, and quartz-porphyry lavas. In Brittany, for example, Dr. Barrois has found a remarkable series of older Palæozoic diabases and porphyrites with tuffs and agglomerates. He distinguishes four principal periods of eruption—1. Cambrian and Lower Silurian; 2. Middle and Upper Silurian; 3. Upper Devonian; 4. Carboniferous.[2] The Permian period was marked in Germany and also in the south of France by the discharge of great masses of various quartz-porphyries. The Triassic period likewise witnessed numerous eruptions. But from that period onward the same remarkable quiescence appears to have reigned all over Europe, which characterised the geological history of Britain during Mesozoic time.[3] In Tertiary time a prodigious outpouring of lavas, both acid and basic, continued from the Miocene epoch down even perhaps to the historic period. Examples of this great series are met with in Central France, the Eifel, Italy,[1] Bohemia, and Hungary, almost to the existing period.[2] Recent research has brought to light evidence of a long succession of Tertiary and post-Tertiary volcanic outbursts in Western America (Nevada, Oregon, Idaho, Utah, &c.) Contemporaneous volcanic rocks are associated with Palæozoic, Secondary, and Tertiary formations in New Zealand, and volcanic action there is not yet extinct.

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[1] For a detailed summary of the volcanic history of Britain, see Presidential addresses to the Geological Society, *Quart. Journ. Geol. Soc.* xlvii. xlviii. (1891-92).

[2] *Carte Géol. détaill. France*, No. 7, 1889.

[3] Some trifling exceptions to this general statement are said to occur C. E. M. Rohrbach

Thus it can be shown that, within the same comparatively limited geographical space, volcanic action has been rife at intervals during a long succession of geological ages. Even round the sites of still active vents, traces of far older eruptions may be detected, as in the case of the existing active volcanoes of Iceland, which rise from amid Tertiary lavas and tuffs. Volcanic action, which now manifests itself so conspicuously along certain lines, seems to have continued in that linear development for protracted periods of time. The actual vents have changed, dying in one place and breaking out in another, yet keeping on the whole along the same tracts. Taking all the manifestations of volcanic action together, both modern and ancient, we see that the subterranean forces have operated along great lines in the earth's crust, and that the existing volcanoes form but a small proportion of the total number of once active vents.

Looking broadly at the geological history of volcanic action we observe that, while there is evidence of the protrusion of both acid and basic materials from the remotest periods, the earlier discharges were preponderantly acid. In Britain, for example, the vast piles of lavas ejected during the Silurian period were mainly of a felsitic character, though considerable accumulations of andesites were not wanting. On the other hand, the wide sheets of lava poured out in this country during Tertiary time were chiefly basalts, the acid protrusions occurring for the most part as dykes and bosses. A similar broad sequence has been observed in other countries.

When, however, we proceed to consider more closely the nature of the successive eruptions during the continuance of one of the volcanic periods of which records are preserved among the geological formations, we discover proofs of a remarkable variation in the character of the lavas.[3]

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describes Cretaceous teschenites and diabases in Silesia (*Tschermak's Min. Mittheil.* vii. (1885), p. 15). P. Choffat refers to Cenomanian eruptions in Portugal (*Journ. Sciencias Math. Phys. Natur*, Lisbon, 1884). A. E. Lagorio has found in the Crimea a series of sheets, dykes, and bosses, ranging from nevadites to basalts.

[1] For early and classical accounts of the Italian volcanic districts, see Spallanzani's 'Voyages dans les deux Siciles,' and Breislak's 'Voyages Physiques et Lythologiques dans la Campanie.' Consult also Mercalli's 'Vulcani, &c.,' and Johnston-Lavis' 'South Italian Volcanoes,' already cited.

[2] For a recent attempt to give a stratigraphical and geographical view of the distribution of igneous rocks in Europe, see M. Bertrand, *Bull. Soc. Géol. France*, xvi. (1888), p. 573.

[3] In some volcanoes (*e.g.* Teneriffe) the lower lavas are heavier and more basic than the upper.

Various observers have noticed that volcanic rocks have succeeded each other in a certain order in different regions. Baron von Richthofen deduced from observations in Europe and America a general sequence of volcanic succession, which he arranged in the following order:—1. Propylite; 2. Andesite; 3. Trachyte; 4. Rhyolite; 5. Basalt.[1] This sequence he believed to be seldom or never complete in any one locality; sometimes only one member of the series may be found; but when two or more occur they follow, in his opinion, this sequence, basalt being everywhere the latest of the series. The subject has been more recently discussed by M. Bertrand, who remarks that in Europe each of the great areas of plication has given rise to the formation of eruptive rocks of every composition and structure. He recognises a recurrence of the phenomena in successive geological periods, and speaks of a definite order of eruptions in the same series.[2]

The great volcanic series of Auvergne presents a marvellous succession of varied eruptions within a limited region during what was probably a single volcanic period. The first eruptions appear to have been basalts, and rocks of similar character reappeared again and again in later stages of the history, the intervening eruptions consisting of phonolites, trachytes, rhyolites, or andesites. The latest lavas were scoriaceous basalts.[3] Among the later Palæozoic volcanic eruptions of Britain a more definite and regular recurrence of rocks appears to be traceable. The earlier lavas of the Old Red Sandstone and Carboniferous series were generally either intermediate or basic, sometimes remarkably basic, while the late protrusions were decidedly acid. At the one end we find basalts or diabases and picrites, followed sometimes by copious outpourings of andesites, while at the other end come intrusions of felsites and quartz-porphyries. Again, among the Tertiary lavas, the basalts of the great plateaux are pierced by bosses and dykes of granophyre and allied acid rocks. In these various examples the facts point to some gradual change in the composition of the subterranean magma during the lapse of a single volcanic period—a change in which there was a separation of basic constituents and the discharge of more basic lavas, leaving a more acid residuum to be erupted towards the end of the activity.[4]

§ 5. Causes of Volcanic Action.

The *modus operandi* whereby the internal heat of the globe manifests itself in volcanic action is a problem to which as yet no satisfactory solution has been found. Were this action merely an expression of the intensity of the heat, we might expect it to have manifested itself in a far more powerful manner in former periods, and to exhibit a regularity and continuity commensurate with the exceedingly slow diminution of the earth's temperature. But there is no geological evidence in favour of greater volcanic intensity in ancient than in more recent periods; on the contrary, it may be doubted whether any of the Palæozoic volcanoes equalled in magnitude those of Tertiary and perhaps even post-Tertiary times. On the other hand, no feature of volcanic action is more conspicuous than its spasmodic fitfulness.[1]

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[1] 'The Natural System of Volcanic Rocks,' *Californ. Acad. Sci.* 1868.

[2] *Bull. Soc. Géol. France*, xvi. (1888), p. 611.

[3] *Carte Géol. détaill. France*, Feuille 166 (Clermont Ferrand).

[4] *Quart. Journ. Geol. Soc.* vol. xlviii. (1892), p. 177.

As physical considerations negative the idea of a comparatively thin crust, surmounting a molten interior whence volcanic energy might be derived (*ante*, p. 53), geologists have found themselves involved in great perplexity to explain volcanic phenomena, for the production of which a source of no great depth would seem to be necessary. Some have supposed the existence of pools or lakes of liquid lava lying beneath the crust, and at an inconsiderable depth from the surface. Others have appealed to the influence of the contraction of the earth's mass, assuming the contraction to be now greater in the outer than in the inner portions, and that the effect of this external contraction must be to squeeze out some of the internal molten matter through weak parts of the crust.[2]

That volcanic action is one of the results of terrestrial contraction can hardly be doubted, though we are still without satisfactory data as to the connection between the cause and the effect. It will be observed that volcanoes occur chiefly in lines along the crests of terrestrial ridges. There is probably, therefore, a connection between the elevation of these ridges and the extravasation of molten rock at the surface. The formation of continents and mountain-chains has already been referred to as probably consequent on the subsidence and readjustment of the cool outer shell of the planet upon the hotter and more rapidly contracting nucleus. Every such movement, by relieving pressure on regions below the axis of elevation, will tend to bring up molten rock nearer the surface, and thus to promote the formation and continued activity of volcanoes.

The fissure-eruptions, wherein lava has risen in innumerable rents in the ground across the whole breadth of a country, and has been poured out at the surface over areas of many thousand square miles, flooding them sometimes to a depth of several thousand feet, undoubtedly prove that molten rock existed at some depth over a large extent of territory, and that by some means still unknown, it was forced out to the surface (*ante*, p. 256). In investigating this subject, it would be important to discover whether any evidence of great terrestrial crumpling or other movement of the crust can be ascertained to have taken place about the same geological period as a stupendous outpouring of lava—

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[1] Consult Dana, 'Characteristics of Volcanoes,' p. 15 *et seq.* Dutton, *U. S. Geol. Rep.* 1882-83, p. 183 *et seq.* Prestwich, *Proc. Roy. Soc.* xli. (1886), p. 117. Lowl, *Jahrb. Geol. Reichsanst.* 1886, p. 315.

[2] Cordier, for example, calculated that a contraction of only a single millimetre (about $\frac{1}{25}$th of an inch) would suffice to force out to the surface lava enough for 500 eruptions, allowing 1 cubic kilometre (about 1300 million cubic yards) for each eruption. Prof. Prestwich invokes a slight contraction of the crust as the initial cause of volcanic action. *Brit. Assoc.* 1881, Sects. p. 610.

whether, for example, the great lava-fields of Idaho may have had any connection with contemporaneous flexure of the North American mountain-system, or whether the basalt-plateaux of Antrim, Scotland, Faröe, and Iceland may possibly have been in their origin sympathetic with the post-Eocene upheaval of the Alps or other Tertiary movements in Europe. The most striking instance of an apparent connection between such terrestrial disturbances and volcanic phenomena is that supplied by the great semicircle of eruptions that sweeps from Central France by the Eifel, Hochgau, and Bohemia into Hungary, and which has been referred to the dislocations consequent on the upheaval of the Alps.[1]

In the ordinary phase of volcanic action, marked by the copious evolution of steam and the abundant production of dust, slags, and cinders, from one or more local vents, the main proximate cause of volcanic excitement is obviously the expansive force exerted by vapours dissolved in the molten magma from which lavas proceed. Whether and to what extent these vapours are parts of the aboriginal constitution of the earth's interior, or are derived by descent from the surface, is still an unsolved problem. The abundant occlusion of hydrogen in meteorites, and the capacity of many terrestrial substances, notably melted metals, to absorb large quantities of gases and vapours without chemical combination, and to emit them on cooling with eruptive phenomena, not unlike those of volcanoes, have led some observers to conclude that the gaseous ejections at volcanic vents are portions of the original constitution of the magma of the globe, and that to their escape the activity of volcanic vents is due. Prof. Tschermak in particular has advocated this opinion, and it is meeting with increasing acceptance.[2]

On the other hand, since so large a proportion of the vapour of active volcanoes consists of steam, many geologists have urged that this steam has in great measure been supplied by the descent of water from above ground. The floor of the sea and the beds of rivers and lakes are all leaky. Moreover, during volcanic eruptions and earthquakes, fissures no doubt open under the sea, as they do on land, and allow the oceanic water to find access to the interior.[3] Again, rain sinking beneath the surface of the land, percolates down cracks and joints, and infiltrates through the very pores of the rocks. The presence of nitrogen among the gaseous discharges of volcanoes may indicate the decomposition of water containing atmospheric gases. The abundant sublimations of chlorides are such as might probably result from the decomposition of sea-water. To some extent surface-waters doubtless do reach the volcanic magma.

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[1] Suess, 'Autlitz der Erde,' i. p. 358, pl. iii. ; Julien, *Annuaire du Club Alpin*, 1879-80, p 446 ; Michel-Lévy, *Bull. Soc. Géol. France*, xviii. (1890), pp 690, 841.

[2] He has suggested that if 190 cubic kilometres, of the constitution of cast iron, be supposed to solidify annually, and to give off 50 times its volume of gases, it would suffice to maintain 20,000 active volcanoes. *Sitz. Akad. Wissen. Wien*, lxxv. (1877), p. 151. Reyer ('Beitrag zur Physik der Eruptionen,' Vienna, 1877) advocates the same view.

[3] Professor Moseley mentions that during a submarine eruption off Hawaii in 1877 "a fissure opened on the coast of that island, from a few inches to three feet broad, and in some places the water was seen pouring down the opening into the abyss below." 'Notes by a Naturalist on the "Challenger,"' p. 503.

Whatever may be its source, we cannot doubt that to the enormous expansive force of superheated water (or of its component gases, dissociated by the high temperature), in the molten magma at the roots of volcanoes, the explosions of a crater and the subsequent rise of a lava-column are mainly due. The water or gas dissolved in the lava is retained there by the enormous overlying pressure of the lava-column, but when the molten material is brought up to the surface the pressure is relieved and the water vaporizes and escapes. Where the relief is rapid the effect may be to froth up the lava into a pasty mass of pumice, while where it is sudden and extreme the escape of the water-vapour may be by an explosive discharge.

It has been supposed that, somewhat like the reservoirs in which hot water and steam accumulate under geysers, reservoirs of molten rock receive a constant influx of water from the surface, which cannot escape by other channels, but is absorbed by the internal magma at an enormously high temperature and under vast pressure. In the course of time, the materials filling up the chimney are unable to withstand the upward expansion of this imprisoned vapour or water-substance, so that, after some premonitory rumblings, the whole opposing mass is blown out, and the vapour escapes in the well-known masses of cloud. Meanwhile, the removal of the overlying column relieves the pressure on the lava underneath, saturated with vapours or superheated water. This lava therefore begins to rise in the funnel until it forces its way through some weak part of the cone, or pours over the top of the crater. After a time, the vapour being expended, the energy of the volcano ceases, and there comes a variable period of repose, until a renewal of the same phenomena brings on another eruption. By such successive paroxysms, the forms of the internal reservoirs and tunnels may be changed; new spaces for the accumulation of superheated water being opened, whence in time fresh volcanic vents issue, while the old ones gradually die out.

An obvious objection to this explanation is the difficulty of conceiving that water should descend at all against the expansive force within. But Daubrée's experiments have shown that, owing to capillarity, water may permeate rocks against a high counter-pressure of steam on the further side, and that so long as the water is supplied, whether by minute fissures or through pores of the rocks, it may, under pressure of its own superincumbent column, make its way into highly heated regions.[1] Experience in deep mines, however, rather goes to show that the permeation of water through the pores of rocks gets feebler as we descend.

Reference may be made here to a theory of volcanic action in which the influence of terrestrial contraction as the grand source of volcanic energy was insisted upon by the late Mr. Mallet.[2] He maintained that all the present manifestations of hypogene action are due directly to the more rapid contraction of the hotter internal mass of the earth and the consequent crushing in of the outer cooler shell. He pointed to the admitted difficulties in the way of connecting volcanic phenomena with the existence of internal lakes of liquid matter, or of a central ocean of molten rock. Observations made by him, on the effects of the earthquake shocks accompanying the volcanic eruptions of Vesuvius and of Etna, showed that the focus of disturbance could not be more than a few miles deep; that, in relation to the general mass of the globe, it was quite superficial, and could not possibly have lain under a crust of 800 miles or upwards in thickness. The occurrence of volcanoes in lines, and especially along some of the great mountain-chains of the planet, was likewise dwelt upon by him as a fact not satisfactorily explicable on any previous hypothesis of volcanic energy. But he contended that all these difficulties disappear when once the simple idea of cooling and contraction is adequately realised. "The secular cooling of the globe," he remarks, "is always going on, though in a very slowly descending ratio. Contraction is therefore constantly providing a store of energy to be expended in crushing parts of the crust, and through that providing for the volcanic heat. But the crushing itself does not take place with uniformity; it necessarily acts *per saltum* after accumulated pressure has reached the necessary amount at a given point, where some of the pressed mass, unequally pressed as we must assume it, gives way, and is succeeded perhaps by a time of repose, or by the transfer of the crushing action elsewhere to some weaker point. Hence, though the magazine of volcanic energy is being constantly and steadily replenished by secular cooling, the effects are intermittent." He offered an experimental proof of the sufficiency of the store of heat produced by this internal crushing to cause all the phenomena of existing volcanoes.[1] The slight comparative depth of the volcanic foci, their linear arrangement, and their occurrence along lines of dominant elevation become, he contended, intelligible under this hypothesis. For since the crushing in of the crust may occur at any depth, the volcanic sources may vary in depth indefinitely; and as the crushing will take place chiefly along lines of weakness in the crust, it is precisely in such lines that crumpled mountain-ridges and volcanic funnels should appear. Moreover, by this explanation its author sought to harmonise the discordant observations regarding variations in the rate of increase of temperature downward within the earth, which have already been cited and referred to unequal conductivity in the crust (p. 51). He pointed out that in some parts of the crust the crushing must be much greater than in other parts; and since the heat "is directly proportionate

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[1] Daubrée, 'Géologie Expérimentale,' p. 274 (criticised adversely by Fisher, 'Physics of Earth's Crust,' 2nd ed. p. 144). Tschermak, cited on previous page. Reyer, 'Beitrag zur Physik der Eruptionen,' § i.

[2] *Phil. Trans.* 1873. See also Daubrée's experimental determination of the

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quantity of heat evolved by the internal crushing of rocks. 'Géologie Expérimentale,' p. 448. For an adverse criticism of Mallet's view, see Fisher, *op. cit.* chap. xxii.

[1] The elaborate and careful experimental researches of this observer will reward attentive perusal. Mallet estimates from experiment the amount of heat given out by the crushing of different rocks (syenite, granite, sandstone, slate, limestone), and concludes that a cubic mile of the crust taken at the mean density would, if crushed into powder, give out heat enough to melt nearly 3½ cubic miles of similar rock, assuming the melting-point to be 2000° Fahr.

to the local tangential pressure which produces the crushing and the resistance thereto," it may vary indefinitely up to actual fusion. So long as the crushed rock remains out of reach of a sufficient access of subterranean water, there would, of course, be no disturbance. But if, through the weaker parts, water enough should descend and be absorbed by the intensely hot crushed mass, it would be raised to a very high temperature, and, on sufficient diminution of pressure, would flash into steam and produce the commotion of a volcanic eruption.

This ingenious theory requires the operation of sudden and violent movements, or at least that the heat generated by the crushing should be more than can be immediately conducted away through the crust. Were the crushing slow and equable, the heat developed by it might be so tranquilly dissipated that the temperature of the crust would not be sensibly affected in the process, or not to such an extent as to cause any appreciable molecular rearrangement of the particles of the rocks. But an amount of internal crushing insufficient to generate volcanic action may have been accompanied by such an elevation of temperature as to induce important changes in the structure of rocks, such as are embraced under the term "metamorphic."

There is, indeed, strong evidence that, among the consequences arising from the secular contraction of the globe, masses of sedimentary strata, many thousands of feet in thickness, have been crumpled and crushed, and that the crumpling has often been accompanied by such an amount of heat and evolution of chemical activity as to produce an interchange and rearrangement of the elements of the rocks,—this change sometimes advancing perhaps to the point of actual fusion. (See *postea*, p. 298, and Book IV. Part VIII.) There is reason to believe that some at least of these periods of intense terrestrial disturbance have been followed by periods of prolonged volcanic action in the disturbed areas. Mr. Mallet's theory is thus, to some extent, supported by independent geological testimony. The existence, however, of large reservoirs of fused rock, at a comparatively small depth beneath the surface, may be conceived as probable, apart from the effects of crushing. The connection of volcanoes with lines of elevation, and consequent weakness in the earth's crust, is what might have been anticipated on the view that the nucleus, though practically solid, is at such a temperature and pressure that any diminution of the pressure, by corrugation of the crust or otherwise, will cause the subjacent portion of the nucleus to melt. Along lines of elevation the pressure is relieved, and consequent melting may take place. On these lines of weakness and fracture, therefore, the conditions for volcanic excitement may be conceived to be best developed, whether arising from the explosive energy of water dissolved in the magma or from water descending to the intensely heated materials underneath the crust. The periodicity of eruptions may thus depend upon the length of time required for the storing up of sufficient steam, and on the amount of resistance in the crust to be overcome. In some volcanoes, the intervals of activity, like those of many geysers, return with considerable regularity.

In other cases, the shattering of the crust, or the upwelling of vast masses of lava, or the closing of subterranean passages for the descending water, or other causes may vary the conditions so much, from time to time, that the eruptions follow each other at very unequal periods, and with very discrepant energy. Each great outburst exhausts for a while the vigour of the volcano, and an interval is needed for the renewed accumulation of vapour.

But beside the mechanism by which volcanic eruptions are produced, further problems are presented by the varieties of materials ejected, by the differences which these exhibit at neighbouring vents, even sometimes in successive eruptions from the same vent, by the alternation or recurrence of lavas from basic to acid in the continuance of a single volcanic period, and by the repetition of a similar cycle in successive periods. Observations are yet needed from a larger number of ancient volcanic districts and in greater detail, before these problems can be satisfactorily discussed and solved. It is obvious that in such a great series of eruptions as that of Central France, where over a comparatively limited area an alternation of basic and acid lavas has been many times repeated, the subterranean magma must have undergone a succession of changes in composition. Perhaps a definite cycle of such alternations may be made out. The sequence from basic to acid protrusions, observable among the British Palæozoic volcanic rocks, is suggestive of a separation of the more basic constituents of the magma with consequent increasing acidity of the residue. The earliest lavas mark the more basic condition of the magma, while the latest felsite and quartz-porphyry intrusions show its impoverishment in bases at the close of a volcanic period. During the interval before the next period the magma had in some way been renewed, for when eruptions began anew they were once more basic. But by the close of the volcanic activity the magma had again lost a large proportion of its basic constituents and had become decidedly acid.

Reference has already (p. 61) been made to the speculation of Durocher as to the existence within the crust of an upper siliceous layer with a mean of 71 per cent of silica, and a lower basic layer with about 51 per cent of silica. Bunsen also came to the conclusion that volcanic rocks are mixtures of two original normal magmas—the normal trachytic (with a mean of 76·67 silica), and the normal pyroxenic (with a mean of 47·48 silica). The varying proportions in which these two original magmas have been combined are, in Bunsen's view, the cause of the differences of volcanic rocks. We may conceive these two layers to be superposed upon each other, according to relative densities, and the composition of the last material erupted at the surface to depend upon the depth from which it has been derived.[1] The earliest explosions may be supposed to have taken place usually from the upper lighter and more siliceous layer, and the lavas ejected would consequently be in general acid, while later eruptions, reaching down to deeper and heavier zones of the magma, brought up such basic lavas as basalt. Certainly the general similarity of the volcanic rocks all over the globe would appear to prove that there must be considerable uniformity of composition in the zones of intensely hot material from which volcanic rocks are derived.[1]

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[1] See R. Bunsen, *Pogg. Ann.* lxiii. (1851), p. 204; Sartorius von Waltershausen, 'Sicilien und Island,' p. 416; Reyer, 'Beitrag zur Physik der Eruptionen,' iii. Scrope had long before suggested a classification of volcanic rocks into Trachyte, Greystone, and Basalt, *Journ. Science*, xxi.

Many difficulties, however, remain yet to be explained before our knowledge of volcanic action can be regarded as more than rudimentary. In Book IV. Part VII. a description is given of the part volcanic rocks have played in building up what we see of the earth's crust, and the student will there find other illustrations of facts and deductions which have been given in the previous pages.

Section ii. Earthquakes.[2]

By the more delicate methods of observation which have been invented in recent years, it has been ascertained that the ground beneath our feet is apparently everywhere subject to continual slight tremors and to minute pulsations of longer duration. The old expression "terra firma" is not only not strictly true, but in the light of modern research seems singularly inappropriate. Rapid changes of temperature and atmospheric pressure, the fall of a shower of rain, the patter of birds' feet, and still more the tread of larger animals, produce tremors of the ground which, though exceedingly minute, are capable of being made clearly audible by means of the microphone and visible by means of the galvanometer. Some tremors of varying intensity and apparently of irregular occurrence, may be due to minute movements or displacements in the crust of the earth. Less easily traceable are the slow pulsations of the crust, which in many cases are periodic, and may depend on such causes as the diurnal oscillation of the thermal or barometric conditions of the atmosphere, the rise and fall of the tides, &c. So numerous and well marked are these tremors and pulsations, that the delicate observations which were set on foot to determine the lunar disturbance of gravity had to be abandoned, for it was found that the minute movements sought for were wholly eclipsed by these earth tremors.[1]

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[1] In the memoir by Captain Dutton, cited in a previous note, the hypothesis is maintained that the order of appearance of the lavas is determined by their relative density and fusibility, the most basic and heaviest, though most easily fused, requiring the highest temperature to diminish their density to such an extent as to permit them to be erupted.

[2] On the phenomena of earthquakes consult Mallet, *Brit. Assoc.* 1847, part ii. p. 30; 1850, p. 1; 1851, p. 272; 1852, p. 1; 1858, p. 1; 1861, p. 201; 'The Great Neapolitan Earthquake of 1857,' 2 vols., 1862; D. Milne, *Edin. New Phil. Journ.* xxxi.-xxxvi.; A. Perrey, *Mém. Couronn. Bruxelles*, xviii. (1844), *Comptes rendus*, lii. p. 146; Otto Volger, 'Untersuchungen uber die Phänomene der Erdbeben in der Schweiz,' Gotha, 1857–8; *Z. Deutsch. Geol. Ges.* xiii. p. 667; R. Falb, 'Grundzuge einer Theorie der Erdbeben und Vulkanensausbruche,' Graz, 1871; 'Gedanken und Studien über den Vulkanismus, &c.,' 1874; Pfaff, 'Allgemeine Geologie als exacte Wissenschaft,' Leipzig, 1873, p. 224. Records of observed earthquakes will be found in the memoirs of Mallet and Perrey; also in papers by Fuchs in *Neues Jahrb.* 1865-1871, and in Tschermak's *Mineralog. Mittheilungen*, 1873 and subsequent years. See also Schmidt, 'Studien über Erdbeben,' 2nd edit.

The term Earthquake denotes any natural subterranean concussion, varying from such slight tremors as to be hardly perceptible up to severe shocks, by which houses are levelled, rocks dislocated, landslips precipitated, and many human lives destroyed. The phenomena are analogous to the shock communicated to the ground by explosions of mines or powder-works. They may be most intelligibly considered as wave-like undulations propagated through the solid crust of the earth. In Mr. Mallet's language, an earthquake may be defined as "the transit of a wave of elastic compression, or of a succession of these, in parallel or intersecting lines through the solid substance and surface of the disturbed country." Mr. Milne has since remarked that the disturbance may also be due to the transit of waves of elastic distortion. The passage of the wave of shock constitutes the real earthquake.

Besides the wave of shock transmitted through the solid crust, waves are also propagated through the air, and, where the site of the impulse is not too remote, through the ocean. Earthquakes originating under the sea are numerous and specially destructive in their effects. They illustrate well the three kinds of waves associated with the progress of an earthquake. These are, 1st, The true earth-wave through the earth's crust; 2nd, a wave propagated through the air, to which the characteristic sounds of rolling waggons, distant thunder, bellowing oxen, &c., are due; 3rd, Two sea-waves, one of which travels on the back of the earth-wave and reaches the land with it, producing no sensible effect on shore; the other an enormous low swell, caused by the first sudden blow of the earth-wave, but travelling at a much slower rate, and reaching land often several hours after the earthquake has arrived.

Amplitude of earth-movements.—The popular conception of the

1879; 'Studien uber Vulkane und Erdbeben,' 1881; Dieffenbach, *Neues Jahrb.* 1872, p. 155; M. S. di Rossi, 'La Meteorologia Endogena,' 2 vols. 1879 and 1882; M. Gatta, 'L'Italia, su vulcani e terremoti,' 1882; J. Milne, 'Earthquakes and other Earth-movements,' 1886, and his beautifully illustrated volume on the Japan Earthquake of October 1891. G. Mercalli, in his 'Vulcani e Fenomeni Vulcanici in Italia' (1883), gives an account of the Italian earthquakes from 1450 B.C. to 1881 A.D.; he separately describes the great Ischian earthquake of 1883: 'L'Isola d'Ischia,' Milan, 1884. Much interesting information will be found in the *Bulletino del Vulcanismo Italiano,* which began to be published in 1874; also in the *Transactions of the Seismological Society of Japan*—a society instituted in the year 1880 for the investigation of earthquake phenomena, especially in Japan, where they are of frequent occurrence. Others papers are quoted in the following pages.

[1] A. d'Abbadie, 'Etudes sur la verticale,' 1872. Plantamour, *Comptes rend.* June 1878, February 1881; *Archives Sciences Phys. Nat.* Geneva, ii. p. 641; v. p. 97; vii. p. 601; viii. p. 551; x. p. 616; xii. (1884), p. 388. G. H. Darwin, *Brit. Assoc.* 1882, p. 95. In this paper Prof. Darwin discusses the amount of disturbance of the vertical near the coasts of continents, caused by the rise and fall of the tide. J. Milne, *Trans. Seismological Soc. Japan,* vi. (1883), p. 1; *Geol. Mag.* 1882, p. 482; *Nature,* xxvi. p. 125. The numerous observations made by Rossi in Italy are summarised by G. Mercalli in his work cited above, p. 332.

extent to which the ground moves to and fro or up and down during an earthquake is a great exaggeration of the truth. As the result of very careful measurement with delicate instruments, there appears to be reason to believe that the horizontal motion at the time of a small earthquake is usually only the fraction of a millimetre, and seldom exceeds three or four millimetres. When the motion rises to five or six millimetres brick and stone chimneys are shattered. Yet even with such an intensity of shock a person walking in an open place might be quite unconscious of any perceptible movement of the ground. The vertical motion also appears to be exceedingly small.[1]

Velocity.—Experiments have been made to determine the velocity of the earth-wave, and its variation with the nature of the material through which it is propagated. Mr. Mallet found that the shock produced by the explosion of gunpowder travelled at the rate per second of 825 feet in sand; 1088 feet in schists, slates, and quartzites; 1306 feet in friable granite; and 1664 feet in solid granite. General Abbot, by observing the effects of the explosion of dynamite and gunpowder, found the velocity of transmission of the shock to vary from 1240 to 8800 feet per second, and to be greatest where the shock is most violent.[2] Observations of the time at which an earthquake has successively visited the different places on its track have shown similar variations in the rate of movement. Thus in the Calabrian earthquake of 1857, the wave of shock varied from 658 to 989 feet per second, the mean rate being 789 feet. The earthquake at Viège in 1855 was estimated to have travelled northwards towards Strasburg at the rate of 2861 feet per second, and southwards towards Turin at a rate of 1398 feet, or less than half the northern speed. The earthquake of 7th October 1874, in northern Italy, travelled at rates varying from 273 to 874 feet per second. That of 12th March 1873 showed a velocity per second of 2734 feet between Ragusa and Venice; 4101 feet from Spoleto to Venice; 601 feet from Perugia to Orvieto; 1640 feet from Perugia to Ancona; and 1640 (or 2188) feet from Perugia to Rome. The rate of the central European earthquake of 1872 was estimated to have been 2433 feet, that of Herzogenrath, June 24, 1877, 1555 feet, that of an earthquake at Travancore, in Southern Hindustan, 656 feet in a second.[3] The most accurate measurements and computations of the velocity of earthquake movements are probably those made by Prof. J. Milne and his associates in Japan. The rates of movement during the Tokio earthquake of 25th October 1881 are estimated to have ranged between 4000 and 9000 feet per second. As the result of prolonged observation, Prof. Milne concludes that "different earthquakes, although they may travel across the same country, have very variable velocities, varying between several hundreds and several thousands of feet per second; that the same earthquake travels more quickly across districts near to its origin than it does across districts which are far removed; and that the greater the intensity of the shock, the greater is the velocity."[1]

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[1] Milne, 'Earthquakes,' pp. 75, 76. An ingenious model in wire has been made by Prof. Sekiya to illustrate the highly complex path pursued by a particle on the surface of the ground during an earthquake at Tokio, Japan, on 15th January 1887.

[2] *Amer. Journ. Sci.* xv. (1878). Prof. J. Milne, experimenting in Japan, has likewise ascertained that a close relation exists between the initial violence of the shock and the velocity of propagation, and that there is a progressive diminution in speed as the wave of shock travels outward from the centre of disturbance. 'Earthquakes,' p. 65.

[3] K. von Seebach, 'Das Mitteldeutsche Erdbeben von 6 Marz, 1872,' Leipzig, 1873. Hofer, *Sitzb. Akad. Wien*, Dec. 1876; A. von Lasaulx, 'Das Erdbeben von Herzogenrath, 22nd Oct. 1873,' Bonn, 1874. 'Das Erdbeben von Herzogenrath, 24 Juni, 1877,' Bonn, 1878. G. C. Laube, on Earthquake of 31st January 1883, at Trautenau, *Jahrb. Geol. Reichs.* 1883, p. 331. H. Credner on the Earthquakes of the Erzgebirge and Vogtland from 1878 to 1884, *Zeitsch. für Naturwiss.* vol. lvii. (1884). F. Wahner, on Agram earthquake of 9

Duration.—The number of shocks in an earthquake varies indefinitely, as well as the length of the intervals between them. Sometimes the whole earthquake only lasts a few seconds: thus the city of Caracas, with its fine churches and 10,000 of its inhabitants, was destroyed in about half-a-minute; Lisbon was overthrown in five minutes. But a succession of shocks of varying intensity may continue for days, weeks, or months. The Calabrian earthquake, which began in February 1783, was continued by repeated shocks for nearly four years until the end of 1786.

Modifying influence of geological structure.—In its passage through the solid terrestrial crust from the focus of origin, the earth-wave must be liable to continual deflections and delays, from the varying geological structure of the rocks. To this cause, no doubt, must be in large measure ascribed the marked differences in the rate of propagation of the same earthquake in different directions. The wave of disturbance, as it passes from one kind of rock to another, and encounters materials of very different elasticity, or as it meets with joints, dislocations, and curvatures in the same rock, must be liable to manifold changes alike in rate and in direction of movement. Even at the surface, one effect of differences of material may be seen in the apparently capricious demolition of certain quarters of a city, while others are left comparatively scatheless. In such cases, it has often been found that buildings erected on loose inelastic foundations, such as sand and clay, are more liable to destruction than those placed upon solid rock. In illustration of this statement the accompanying plan (Fig. 71) of Port Royal, Jamaica, was given by De la Beche[2] to show that the portions of the town which did not disappear during the earthquake of 1692 were built upon solid white limestone, while the parts built on sand were shaken to pieces.[3]

It has been observed that an earthquake shock will pass under a limited area without disturbing it, while the region all around has been affected, as if there were some superficial stratum protected from the

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Nov. 1880, *Sitz. Akad. Wien*, lxxxviii. (1883), p. 15. Di Rossi, 'Meteorologia Endogena,' i. p. 306; P. Serpieri, *Instituto Lombardo*, 1873.

[1] 'Earthquakes,' p. 94.

[2] 'Geological Observer,' p. 426.

[3] The opposite effect has been observed on the island of Ischia, the houses built on loose subsoil generally having suffered much less than the others. There appears, indeed, to be a considerable conflict of testimony on this subject. See Milne, 'Earthquakes,' p. 130.

earth-wave. Humboldt cited a case where miners were driven up from below-ground by earthquake shocks not perceptible at the surface, and on the other hand, an instance where they experienced no sensation of an earthquake which shook the surface with considerable violence.[1] Such facts bring impressively before the mind the extent to which the course of the earth-wave must be modified by geological structure. In some instances, the shock extends outwards from a common centre, so that a series of concentric circles may be drawn round the focus, each of which will denote a certain approximately uniform intensity of shock ("coseismic lines" of Mallet), this intensity, of course, diminishing with distance from the focus. The Calabrian earthquake of 1857 and that of Central Europe in 1872, may be taken in illustration of this central type. In other cases, however, the earthquake travels chiefly along a certain band or zone (particularly along the flanks of a mountain-chain) without advancing far from it laterally. This type of linear earthquake is exemplified by the frequent shocks which traverse Chili, Peru, and Ecuador, between the line of the Andes and the Pacific coast.[2]

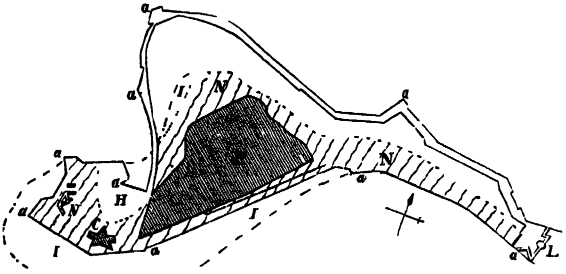

Fig. 71.—Plan of Port Royal, Jamaica, showing the effects of the Earthquake of 1692 (B.)
P C, Portions of the town built on limestone and left standing after the earthquake; *a a*, L, the boundary of the town prior to the earthquake; N N, Ground gained by the drifting of sand up to the end of last century; I L H, Additions from the same cause during the first quarter of the present century

Extent of country affected.—The area shaken by an earthquake varies with the intensity of the shock, from a mere local tract where a slight tremor has been experienced, up to such catastrophes as that of Lisbon in 1755, which, besides convulsing the Portuguese coasts, extended into the north of Africa on the one hand and to Scandinavia on the other, and was even felt as far as the east of North America. Humboldt computed that the area shaken by this great earthquake was four times greater than that of the whole of Europe. The South American earthquakes are remarkable for the great distances to which their effects extend in a linear direction. Thus the strip of country in Peru and Ecuador severely shaken by the earthquake of 1868, had a length of 2000 miles.

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[1] 'Cosmos,' Art. *Earthquakes.*

[2] For a list of Peruvian earthquakes from A.D. 1570 to 1875, see *Geograph. Mag.* IV. (1877), p. 206. The earthquake of 9 May, 1877, at Iquique, and its ocean-wave are described by E. Geinitz, *Nova Act. Ac. Cæs. Leopold. Car.* xl. (1878), pp. 383-444.

Depth of source.—According to Mallet's observations, over the centre of origin the shock is felt as a vertical up-and-down movement (*Seismic vertical*); while, receding from this centre in any direction, it is felt as an undulatory movement, and comes up more and more obliquely. The *angle of emergence*, as he termed it, was obtained by him by taking the mean of observations of the rents and displacements of walls and buildings. In Fig. 72, for example, the wall there represented has been rent by an earthquake which emerged to the surface in the path marked by the arrow.

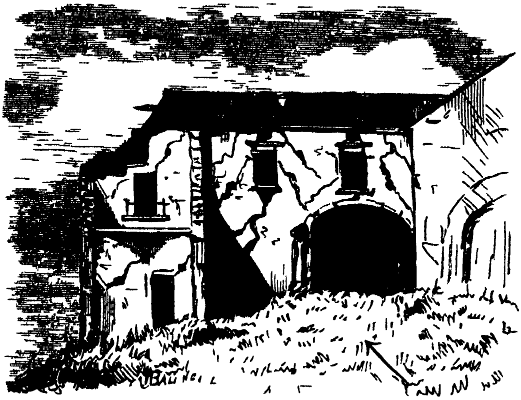

Fig 72 —Wall shattered by an Earthquake, of which the "path of emergence" has been in the direction shown by the arrow (After Mallet)

By observations of this nature, Mallet estimated the approximate depth of origin of an earthquake Let Fig 73, for example, represent a portion of the earth's crust in which at *a* an earthquake arises. The wave of shock will travel outwards in successive spherical shells. At the point *e* it will be felt as a vertical movement, and loose objects, such as paving-stones, may be jerked up into the air, and descend bottom uppermost on their previous sites. At *d*, however, the wave will emerge at a lower angle, and will give rise to an undulation of the ground, and the oscillation of objects projecting above the surface. In rent buildings, the fissures will be on the whole perpendicular to the path of emergence. By a series of observations made at different points, as at *g* and *f*, a number of angles are obtained, and the point where the various lines cut the vertical (*a*) will mark the area of origin of the shock. By this

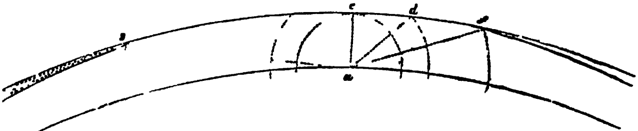

Fig 73 —Mallet's mode of estimation of depth of source of Earthquake movements

means, Mallet computed that the depth at which the impulse of the Calabrian earthquake of 1857 was given was about five miles. As the general result of his inquiries, he concluded that, on the whole, the origin of earthquakes must be sought in comparatively superficial parts of the crust, probably never exceeding a depth of 30 geographical miles. Following another method of calculation, Von Seebach computed that the earthquake which affected Central Europe in 1872 originated at a depth of 9·6 geographical miles; that of Belluno in the same year was estimated by Höfer to have had its source rather more than 4 miles deep; while that of Herzogenrath in 1873 was placed by Von Lasaulx at a depth of about 14½ miles, and that of 1877 in the same region at about 14 miles.[1]

Geological Effects.—These are dependent not only on the strength of the concussion but on the structure of the ground, and on the site of the disturbance, whether underneath land or sea. They include changes superinduced on the surface of the land, on terrestrial and oceanic waters, and on the relative levels of land and sea.

1. Effects upon the soil and general surface of a country.—The earth-wave or wave of shock underneath a country may traverse a wide region and affect it violently at the time, without leaving permanent traces of its passage. Blocks of rock, however, already disengaged from their parent masses on declivities, may be rolled down into the valleys. Landslips are produced, which may give rise to considerable subsequent changes of drainage. In some instances, the surfaces of solid rocks are shattered as if by gunpowder, as was particularly noticed to have taken place among the Primary rocks in the Concepcion earthquake of 1835.[2] It has often been observed also that the soil is rent by fissures which vary in size from mere cracks, like those due to desiccation, up to chasms a mile or more in length and 200 feet or more in depth. Permanent modifications of the landscape may thus be produced. Trees are thrown down, and buried, wholly or in part, in the rents. These superficial effects may, indeed, be soon effaced by the levelling power of the atmosphere. Where, however, the chasms are wide and deep enough to intercept rivulets, or to serve as channels for heavy rain-torrents, they are sometimes further excavated, so as to become gradually enlarged into ravines and valleys, as has happened in the case of rents caused by the earthquakes of 1811-12, in the Mississippi valley. In the earthquake which shook the South Island of New Zealand in 1848, a fissure was formed, averaging 18 inches in width and traceable for a distance of 60 miles parallel to the axis of the adjacent mountain-chain. The subsequent earthquake of 1855, in the same region, gave rise to a fracture which could be traced along the base of a line of cliff for a distance of about 90 miles. Dr. Oldham has described a remarkable series of fissurings which ran parallel with the river of Calhar, Eastern British India,

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[1] See papers by Hofer and A. von Lasaulx, cited on p. 272. For an account of the various methods employed in estimating the depth of origin of earthquakes, see Milne's 'Earthquakes,' chapters x. and xi. Consult also the *Trans. Seismolog. Soc. Japan.*

[2] Darwin, 'Journal of Researches,' 1845, p. 303.

varying with it to every point of the compass and traceable for 100 miles.[1] The great Japanese earthquake of 28th October 1891 gave rise to some remarkable fractures of the ground, in one of which one side was placed permanently at a different level from the other (Fig. 74).

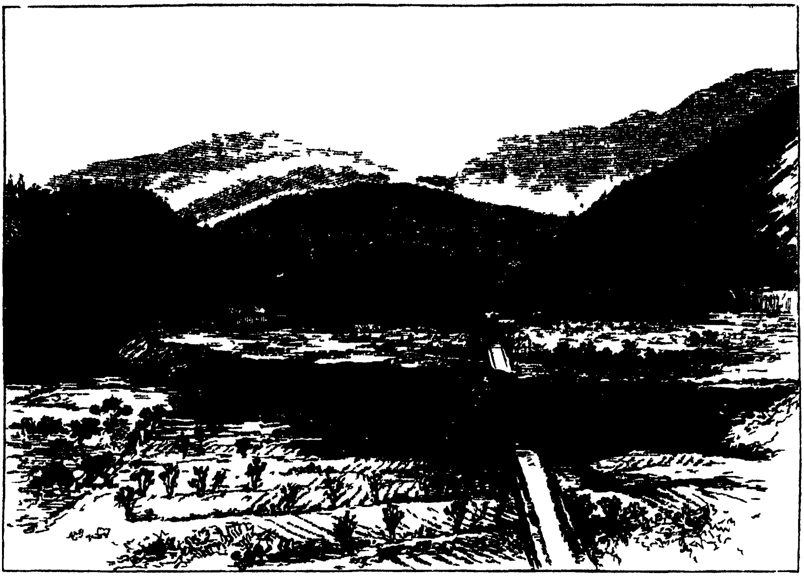

Fig. 74.—Fissure or fault caused by the earthquake of 28th October 1891, in the Neo valley, Japan.

Remarkable circular cavities have been noticed in Calabria and elsewhere, formed in the ground during the passage of the earth-wave. In many cases, these holes serve as funnels of escape for an abundant discharge of water, so that when the disturbance ceases they appear as pools. They are believed to be caused by the sudden collapse of subterranean water-channels and the consequent forcible ejection of the water to the surface. Besides water, discharges of various gases and vapours, sometimes combustible, have been noted at the fissures formed during earthquakes.

2. **Effects upon terrestrial waters.**[2]—Springs are temporarily affected by earthquake movements, becoming greater or smaller in volume, sometimes muddy or discoloured, and sometimes increasing in temperature. Brooks and rivers have been observed to flow with an interrupted course, increasing or diminishing in size, stopping in their flow so as to leave their channels dry, and then rolling forward with increased rapidity. Lakes are still more sensitive. Their waters occasionally rise and fall for several hours, even at a distance of many hundred miles from the centre of disturbance. Thus, on the day of the

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[1] *Q. J. Geol. Soc.* xxviii. p. 257. For a catalogue of Indian Earthquakes down to the end of 1869, see T. Oldham, *Mem. Geol. Surv. India*, xix. part 2.

[2] Kluge, *Neues Jahrb.* 1861, p. 777.

great Lisbon earthquake, many of the lakes of central and north-western Europe were so affected as to maintain a succession of waves rising to a height of 2 or 3 feet above their usual level. Cases, however, have been observed where, owing to excessive subterranean movement, lakes have been emptied of their contents and their beds have been left permanently dry. On the other hand, areas of dry ground have been depressed, and have become the sites of new lakes.

Some of the most important changes in the fresh water of a region, however, are produced by the fall of masses of rock and earth, which, by damming up a stream, may so arrest its water as to form a lake. If the barrier be of sufficient strength, the lake will be permanent; though, from the usually loose, incoherent character of its materials, the dam thrown across the pathway of a stream runs a great risk of being undermined by the percolating water. A sudden giving way of the barrier allows the confined water to rush with great violence down the valley, and to produce perhaps tenfold more havoc there than may have been caused by the original earthquake. When a landslip is of sufficient dimensions to divert a stream from its previous course, the new channel thus taken may become permanent, and a valley may be cut out or widened.

3. Effects upon the sea.—The great sea-wave propagated outward from the centre of a sub-oceanic earthquake and reaching the land after the earth-wave has arrived there, gives rise to much destruction along the maritime parts of the disturbed region. When it approaches a low shore, the littoral waters retreat seawards, sucked up, as it were, by the advancing wall of water, which, reaching a height of sometimes 60 feet or more, rushes over the bare beach and sweeps inland, carrying with it everything which it can dislodge and bear away. Loose blocks of rock are thus lifted to a considerable distance from their former position, and left at a higher level. Deposits of sand, gravel, and other superficial accumulations are torn up and swept away, while the surface of the country, as far as the limit reached by the wave, is strewn with débris. If the district has been already shattered by the passage of the earth-wave, the advent of the great sea-wave augments and completes the devastation. The havoc caused by the Lisbon earthquake of 1755, and by that of Peru and Ecuador in 1868, was much aggravated by the co-operation of the oceanic wave. Where the wave breaks on land rising out of deep water little damage may be done.

4. Permanent changes of level.—It has been observed, after the passage of an earthquake, that the level of the disturbed country has sometimes been changed. Thus after the terrible earthquake of 19th November 1822, the coast of Chili, for a long distance, was found to have risen from 3 to 4 feet, so that along shore, littoral shells were exposed still adhering to the rocks, amid multitudes of dead fish. The same coast-line has been further upraised by subsequent earthquake shocks. On the other hand, many instances have been observed where the effect of an earthquake has been to depress permanently the disturbed ground. For example, by the Bengal earthquake of 1762, an area of 60

square miles on the coast near Chittagong, suddenly wênt down beneath the sea, leaving only the tops of the higher eminences above water. The succession of earthquakes which in the years 1811 and 1812 devastated the basin of the Mississippi, gave rise to widespread depressions of the ground, over some of which, above alluded to, the river spread so as to form new lakes, with the tops of the trees still standing above the surface of the water.

Distribution of Earthquakes.[1]—While no large space of the earth's surface seems to be free from at least some degree of earthquake-movement, there are regions more especially liable to the visitation. As a rule, earthquakes are most frequent in volcanic districts, the explosions of a volcano being generally preceded or accompanied by tremors of greater or less intensity. In the Old World, a great belt of earthquake disturbance stretches in an east and west direction, along that tract of remarkable depressions and elevations lying between the Alps and the mountains of northern Africa, and spreading eastward so as to enclose the basins of the Mediterranean, Black Sea, Caspian, and Sea of Aral, and to rise into the great mountain-ridges of Central Asia. In this zone lie numerous volcanic vents, both active and extinct or dormant, from the Azores on the west to the basaltic plateaux of India on the east. The Pacific Ocean, surrounded with a vast ring of volcanic vents, has its borders likewise subject to frequent earthquake shocks. Some of the most terrible earthquakes within human experience have been those which have affected the western seaboard of South America.[2] It is worthy of notice that the coasts of the Pacific Ocean more specially liable to convulsions of this nature plunge steeply down into deep water with slopes of one in twenty to one in thirty, while shore-lines such as those of Australia, Scandinavia, and the east of South America, where the slope is no more than from one in fifty to one in two hundred and fifty, are hardly ever affected by earthquakes. It should also be remarked that while earthquakes are apt to occur along the flanks of mountain-chains and to travel along these lines of elevation, they seldom cross a large mountain-chain. In some regions the site of disturbance is not on land but under the sea. This has been clearly established for Japan.[1]

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[1] For European earthquakes an alphabetical catalogue has been compiled by Professor O'Reilly, *Trans. Roy. Irish Academy*, xxviii. (1886), p. 489. Catalogue of British earthquakes, *op. cit.* xxviii. (1884), p. 285. C. Davidson, *Geol. Mag.* 1891, p. 450. *Quart. Jour. Geol. Soc.* xlvii. (1891), p. 618. Detailed observations of the effects of some recent European earthquakes will be found in the following Memoirs. The Andalusian earthquake of 25th Dec. 1884, T. Taramelli and G. Mercalli, *Real. Accad. Lincei*, 1885-86, p. 116, Hébert, *Compt. rend.* 1885, Fouqué, *ibid.* 20th April 1885, and the large quarto volume of reports by the mission specially sent to study the phenomena of this earthquake, *Mémoires Acad. Sci.* 1889 ; the Ligurian earthquake of 23rd Feb. 1887, T. Taramelli and G. Mercalli, *Ann. Ufficio Centrale Meteorolog. Geodinam.* part iv. vol. viii. (1888), *Real. Accad. Lincei*, iv. (1888) ; the Agram earthquake of 9th Nov. 1880, 'Grundzuge der Abyssodynamik, &c.,' by S. Pilar, Agram, 1881 ; the middle German earthquake of 6th March 1872, 'Das Mitteldeutsche Erdbeben von 6 Marz 1872,' by K. von Seebach, Leipzig, 1873. See also the papers cited on pp. 270-273.

[2] The Charleston Earthquake of 31st August 1886, has been fully discussed by Captain Dutton, *Ninth Ann. Report U. S. Geol. Survey*, 1887-88, p. 209. The earthquakes of Central America are discussed by F. de Montessus de Ballore in a Memoir rewarded by the Acad. Sci. Nat. Saone et Loire, and published at Dijon, 1888.

Origin of Earthquakes.—Though the phenomena of an earthquake become intelligible as the results of the transmission of waves of shock arising from a centre where some sudden and violent impulse has been given within the terrestrial crust, the origin of this sudden blow can only be conjectured. Various conceivable causes may, at different times and under different conditions, communicate a shock to the subterranean regions. Such are the sudden flashing into steam of water in the spheroidal state, the sudden condensation of steam, the explosions of a volcanic orifice, the falling in of the roof of a subterranean cavity, or the sudden snap of deep-seated rocks subjected to prolonged and intense strain.

In volcanic regions, the frequent earthquakes which precede or accompany eruptions are doubtless traceable to explosions of elastic vapours, and notably of steam. As earthquakes originate also in districts remote from any active volcano, and, so far as observation shows, at comparatively shallow depths, these cannot be connected with ordinary volcanic action, though it is possible that by movements of molten or highly-heated matter within the crust and its invasion of the upper layer, to which meteoric water in considerable quantities descends, sudden and extensive generation of steam may occasionally take place.[2] In minor cases, where the tremor is comparatively slight and local, we may conceive that the collapse of the roof or sides of some of the numerous tunnels and caverns dissolved out of underground rocks by permeating water may suffice to produce the observed shocks.[3] The copious discharge of materials from a volcanic vent may produce a cavity within the earth, the crushing in of which will give rise to earthquakes. There appears reason to believe that the most convulsive earthquakes originate under the sea, as in the cases of the great Lisbon earthquake and those of Peru, Chili, and Japan. For these it is as yet difficult to imagine an adequate cause. Professor Milne believes that they may be partly due to disturbances of the nature of volcanic explosions, because they originate beneath the sea, and the vibrations have the peculiar rapid inward motion characteristic of the discharge of an explosive like dynamite.[4]

An obvious source of disturbance within the earth is the rupture of rocks within the crust under the intense strain produced by subsidence upon the more rapidly contracting inner hot nucleus. This cause may conceivably affect mountainous areas; but we do not know how it would affect the sea-floor. In mountainous districts, many different degrees of shock, from mere tremors up to important earthquakes, have been observed, and these are not improbably due to sudden more or less extensive fractures of rocks still under great strain.[1] Hoernes, from a study of European earthquake phenomena, concludes that though some minor earth-tremors may be due to the collapse of underground caverns, and others of local character to volcanic action, the greatest and most important earthquakes are the immediate consequences of the formation of mountains, and he connects the lines followed by earthquakes with the structural lines of mountain-axes.[2]

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[1] Milne, 'Earthquakes,' p. 227.

[2] Pfaff, 'Allgemeine Geologie als exacte Wissenschaft,' p. 230.

[3] In the Visp Thal, Canton Wallis, for example, where there are some twenty springs carrying up gypsum in solution (one of them to the extent of 200 cubic metres annually), continued rumblings and sharp shocks are from time to time experienced. In July and August, 1855, these movements lasted upwards of a month, and gave rise to the fissuring of buildings and the precipitation of landslips. In the honeycombed limestone tract of the Karst, also, earthquakes of varied intensity are of constant occurrence.

[4] 'Earthquakes,' p. 281.

From what was stated at the beginning of the present section, it is evident that where the earth's crust in any region is in a critical condition of equilibrium, some connection may be expected to be traceable between the frequency of earthquakes and the earth's position with regard to the moon and sun, on the one hand, and changes of atmospheric conditions, on the other. A comparison of the dates of recorded earthquakes seems to bear out the following conclusions; 1st. An earthquake maximum occurs about the time of new moon; 2nd. Another maximum appears two days after the first quarter; 3rd. A diminution of activity occurs about the time of full moon; 4th. The lowest earthquake minimum is on the day of the last quarter.[3] There is likewise observable a seasonal maximum and minimum, earthquakes over most of the northern hemisphere occurring most frequently in winter, and least frequently in summer.[4] Out of 656 earthquakes chronicled in France up to the year 1845, three-fifths took place in the winter, and two-fifths in the summer months. In Switzerland they have been observed to be about three times more numerous in winter than in summer. The same fact is remarked in the history even of the slight earthquakes in Britain. A daily maximum appears to occur about 2.30 A.M., and a minimum about three-quarters of an hour after noon. No connection has yet been satisfactorily established between the occurrence of earthquakes and sun-spots. The greater frequency of earthquakes in winter might be expected to indicate a relation between their occurrence and atmospheric pressure, and possibly earthquakes are more frequent with a low than with a high barometer.[5]

Section iii. Secular Upheaval and Depression.

Besides scarcely perceptible tremors and more or less violent movements due to earthquake-shocks, the crust of the earth is generally believed to undergo in many places oscillations of an extremely quiet and uniform character, sometimes in an upward, sometimes in a downward direction. So tranquil may these changes be, as to produce from day to day no appreciable alteration in the aspect of the ground affected, so that only after the lapse of several generations, and by means of careful measurements, can they really be proved. Indeed, in the interior of a country nothing but a series of accurate levellings from some unmoved datum-line might detect the change of level, unless the effects of the terrestrial disturbance showed themselves in altering the drainage. Only along the sea-coast is a ready measure afforded of any such movement.

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[1] See *postea*, p. 311. Suess, 'Entstehung der Alpen,' Vienna, 1875.

[2] "Erdbeben Studien," *Jahrb. Geol. Reichs.* xxviii. (1878), p. 448.

[3] J. F. J. Schmidt, "Studien uber Erdbeben," 2nd ed. (1879), p. 18.

[4] *Ibid.* p. 20. See the works of Perrey cited on p. 270.

[5] Schmidt, *op. cit.* p. 23. F. Groger, *Neues Jahrb.* 1878, p. 928. There does not appear to be any marked connection between the state of the barometer and the occurrence of earthquakes in Japan—J. Milne, 'Earthquakes,' p. 268.

It is customary in popular language to speak of the sea rising or falling relatively to the land. We cannot conceive of any possible augmentation of the oceanic waters, nor of any diminution, save what may be due to the extremely slow processes of abstraction by the hydration of minerals and absorption into the earth's interior. Any changes, therefore, in the relative levels of sea and land must be due to some readjustment in the form either of the solid globe or of its watery envelope or of both. Playfair argued at the beginning of this century that no subsidence of the sea-level could be local, but must extend over the globe.[1] But it is now recognised that what is called the sea-level cannot possess the uniformity formerly attributed to it; that on the contrary it must be liable to local distortion from the attractive influence of the land. Not only so, but the level of the surface of large inland sheets of water must be affected by the surrounding high lands.

Mr. R. S. Woodward, whose recent memoir on this subject has been cited (p. 35) has calculated that in a lake 140 miles broad and 1000 feet deep in the middle, the difference of level of the water-surface at the centre and at the margin may amount to between three and four feet.[2] As already stated he has further computed that the effect of the continents of Europe and Asia at the centre in disturbing the sea-level must amount to about 2900 feet, if we suppose that there is no deficiency of density underneath the continent, and to only about 10 feet if we suppose that the very existence of the continent implies such a deficiency.[3]

Various suggestions have been made regarding possible causes of alteration of the sea-level. (1) A shifting of the present distribution of density within the nucleus of the planet would affect the position and level of the oceans (*ante*, p. 47). (2) As permanent snow and ice represent so much removed from the general body of water on the globe, any large increase or diminution in the extent and thickness of the polar ice-caps must cause a corresponding variation in the sea-level (*ante*, p. 20). (3) A change in the earth's centre of gravity, such as might result from the accumulation of large masses of snow and ice as an ice-cap at one of the poles, has been already referred to (p. 20) as tending to raise the level of the ocean in the hemisphere so affected, and to diminish it in a corresponding measure elsewhere. The return of the ice into the state of water would produce an opposite effect. The attractive influence of the ice-sheets of the Glacial Period upon the sea-level over the northern hemisphere has been discussed by various mathematicians, especially by Croll, Pratt, Heath, and Lord Kelvin. Considerable differences appear in their results, according to the conditions which they postulate, but they agree that a decided elevation of the sea-level must be attributed to the accumulation of thick masses of snow and ice. The rise of the sea-level along the border of an ice-cap of 38° angular radius and 10,000 feet thick in the centre is estimated at from 139 to 573 feet.[1] (4) A still further conceivable source of geographical disturbance is to be found in the fact that, as a consequence of the diminution of centrifugal force owing to the retardation of the earth's rotation caused by the tidal wave, the sea-level must have a tendency to subside at the equator and rise at the poles.[2] A larger amount of land, however, need not ultimately be laid bare at the equator, for the change of level resulting from this cause would be so slow that, as Dr. Croll has pointed out, the general degradation of the surface of the land might keep pace with it and diminish the terrestrial area as much as the retreat of the ocean tended to increase it. The same writer has further suggested that the waste of the equatorial land, and the deposition of the detritus in higher latitudes, may still further counteract the effects of retardation and the consequent change of ocean-level. (5) Some geologists have supposed that where the earth's crust is loaded with thick deposits of sediment or massive ice-sheets it will tend to sink, while on the other hand denudation by unloading it promotes upheaval.

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[1] 'Illustrations of the Huttonian Theory,' 1802. The same conclusion was announced by L. von Buch, 'Reise durch Norwegen und Lapland,' 1810.

[2] Bull. U. S. Geol. Surv. No. 48 (1888), p. 59.

[3] *Op. cit.* p. 85. See Stokes, *Trans. Camb. Phil. Soc.* viii. (1849), p. 672; *Sci. Proc. Roy. Dublin Soc.* v. (1887), p. 652.

The balance of evidence at present available seems adverse to any theory which would account for ancient and modern changes in the relative level of sea and land by variations in the figure of the oceanic envelope, save to a limited extent by the attraction caused by extensive masses of upraised land, and possibly in northern and southern latitudes by the attractive influence of large accumulations of snow and ice. Such changes are rather to be regarded as due to movements of the solid crust. The proofs of upheaval and subsidence, though sometimes obtainable from wide areas, are marked by a want of uniformity and a local and variable character, indicative of an action local and variable in its operations, such as the folding of the terrestrial crust, and not regular and widespread, such as might be predicated of any alteration of sea-level. While admitting therefore that, to a certain extent, oscillations of the relative level of sea and land may have arisen from some of the causes above enumerated, we may hold that, on the whole, it is the land which rises and sinks rather than the sea.[1]

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[1] See Croll, 'Climate and Time,' chap. xxiii. xxiv. *Geol. Mag.* 1874. Pratt, 'Figure of the Earth.' D. D. Heath, *Phil. Mag.* xxxi. (1866), pp. 201, 323, xxxii. (1866), p. 34. Thomson (Lord Kelvin), *op. cit.* xxxi. p. 305. A. Penck, *Jahrb. Geograph. Gesel.* Munich, vii. De Lapparent, *Bull. Soc. Géol. France*, xiv. (1886), p. 368, *Revue Générale des Sciences*, May 1890. R. S. Woodward, *Bull. U. S. Geol. Survey*, No 48. Von Drygalski, 'Bewegungen der Kontinente zur Eiszeit,' Berlin, 1889. Prof. Suess believes that the limits of the dry land depend upon certain large indeterminate oscillations of the statical figure of the oceanic envelope; that not only are "raised beaches" to be thus explained, but that there are absolutely no vertical movements of the crust save such as may form part of the plication arising from secular contraction; and that the doctrine of secular fluctuations in the level of the continents is merely a remnant of the old "Erhebungstheorie," destined to speedy extinction. 'Antlitz der Erde,' Leipzig, 1883. Pfaff defends the general opinion against these views in *Zeitsch. Deutsch. Geol. Ges.* 1884.

[2] Croll, *Phil. Mag.* 1868, p. 382. Thomson, *Trans. Geol. Soc. Glasgow*, iii. p. 223.

§ 1. **Upheaval.**—Various maritime tracts of land have been ascertained to have undergone in recent times, or to be still undergoing, what appears to be a gradual elevation above the sea. On the coast of Siberia, for 600 miles to the east of the river Lena, round the islands of Spitzbergen and Novaja Zemlja, along the shores of the Scandinavian peninsula with the exception of a small area at its southern apex, and along a maritime strip of western South America, it has been proved that the sea stands now at a lower level with regard to the land than it formerly did. In searching for proofs of such movements the student must be on his guard against being deceived by any apparent retreat of the sea, which may be due merely to the deposit of gravel, sand, or mud along the shore, and the consequent gain of land. Local accumulations of gravel or "storm beaches," are often thrown up by storms, even above the level of ordinary high-tide mark. In estuaries, also, considerable tracts of low ground are gradually raised above the tide-level by the slow deposit of mud. The following proofs of actual rise of the land are chiefly relied on by geologists.[2]

Evidence from dead organisms.—Rocks covered with barnacles or other littoral adherent animals, or pierced by lithodomous shells, afford presumptive proof of the presence of the sea. A single stone with these creatures on its surface would not be satisfactory evidence, for it might have been cast up by a storm; but a line of large boulders, which had evidently not been moved since the cirripedes and mollusks lived upon them, and still more a solid cliff with these marks of littoral or sub-littoral life upon its base, now raised above high-water mark, would be sufficient to demonstrate a change of level. The amount of this change might be pretty accurately determined by measuring the vertical distance between the upper edge of the barnacle zone upon the upraised rock, and the limit of the same zone on the present shore. By this kind of evidence, the recent uprise of the coast of Scandinavia has been proved. The shell-borings on the pillars of the temple of Jupiter Serapis in the Bay of Naples prove first a depression and then an elevation of the ground to the extent of more than twenty feet.[3] Raised coral-reefs, formed by living species of corals, are a conspicuous feature of the geology of the West Indian Region. The terraces of Barbadoes are particularly striking. In

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[1] For the arguments against the view above adopted and in favour of the doctrine that the increase of the land above sea-level is due to the retirement of the sea, see H. Trautschold, *Bulletin Société Imp. des Naturalistes de Moscou*, xlii. (1869), part i. p. 1; 1883, No. 2, p. 341; *Bull. Soc. Géol. France* (3), viii. (1879), p. 134; but more especially Suess, in his great work the 'Antlitz der Erde.'

[2] See "Earthquakes and Volcanoes" (A. G.), Chambers's *Miscellany of Tracts.*

[3] Babbage, *Edin. Phil. Journ.* xi. (1824), 91. J. D. Forbes. *Edin. Journ. Sci.* i. (1829), p. 260. Lyell, 'Principles.' ii. p. 164.

Cuba, a raised coral-reef occurs at a height of 1000 or 1100 feet above the sea.[1] In Peru, modern coral-limestone has been found 2900 or 3000 feet above sea-level.[2] Again, in the Solomon Islands, evidence of recent uprise is furnished by coral reefs lying at a height of 1100 feet,[3] and similar evidence occurs among the New Hebrides at 1500 feet.

The elevation of the sea-bottom can in like manner be proved by dead organisms fixed in their position of growth beneath high-water mark. Thus dead specimens of *Mya truncata* occur on some parts of the coast of the Firth of Forth in considerable numbers, still placed with their siphuncular end uppermost in the stiff clay in which they burrowed. The position of these shells is about high-water mark, but as their existing descendants do not live above low-water mark, we may infer that the coast has been raised by at least the difference between high and low-water mark, or eighteen feet.[4] Dead shells of the large *Pholas dactylus* occur in a similar position near high-water mark on the Ayrshire coast. Even below low-water, examples have been noted, as in the interesting case observed by Sars on the Drobaksbank in the Christiania Fjord, where dead stems of *Oculina prolifera* (L.) occur at depths of only ten or fifteen fathoms. This coral is really a deep-sea form, living on the western and northern coasts of Norway, at depths of one hundred and fifty to three hundred fathoms in cold water. It must have been killed as the elevation of the area brought it up into upper and warmer layers of water.[5] It has even been said that the pines on the edges of the Norwegian snow-fields are dying in consequence of the secular elevation of the land bringing them up into colder zones of the atmosphere.

Any stratum of rock containing marine organisms which have manifestly lived and died where their remains now lie, may be held to prove a change of level between sea and land. In this way it can be shown that most of the solid land now visible to us has once been under the sea. High on the flanks of mountain-chains (as in the Alps and Himalayas), undoubted marine shells occur in the solid rocks.

Sea-worn Caves.—A line of sea-worn caves, now standing at a distance above high-water mark beyond the reach of the sea, affords evidence of recent change of level. In the accompanying diagram (Fig. 75) examples of such caves are seen at the base of the cliff, once the sea-margin, now separated from the tide by a platform of meadow-land.

Raised Beaches furnish one of the most striking proofs of change of level. A beach or space between tide-marks, where the sea is constantly grinding down sand and gravel, mingling with them the remains of shells and other organisms, sometimes piling the deposits up, sometimes sweeping them away out into opener water, forms a familiar terrace or platform on coast-lines skirting tidal seas. When this margin of littoral deposits has been placed above the reach of the waves, the flat terrace thus elevated is known as a "raised beach" (Figs. 75, 76, 77, 78). The former high-water mark then lies inland, and while its sea-worn caves are in time hung with ferns and mosses, the beach across which the tides once flowed furnishes a platform on which meadows, fields, gardens, roads, houses, villages, and towns spring up, while a new beach is made below the margin of the uplifted one. A series of raised beaches may occur at various heights above the sea. Each terrace marks a former lower level of the land with regard to the sea, and probably a lengthened stay of the land at that level, while the intervals between them represent the vertical amount of each variation in the relative levels of sea and land, and show that the interval between the changes was too brief for the formation of terraces. A succession of raised beaches, rising above the present sea-level, may therefore be taken as pointing to a former intermittent upheaval of the country, interrupted by long pauses, during which the general level did not materially change, unless in regions where there is reason to believe that the surface of the sea has undergone a change of level from the accumulation or melting of large masses of snow and ice (*ante*, p. 20).

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[1] A. Agassiz, *Amer. Acad.* xi. (1882), p. 119.

[2] A. Agassiz, *Bull. Mus. Comp. Zool.* vol. iii.

[3] H. B. Guppy, *Nature*, 3rd January 1884.

[4] Hugh Miller's 'Edinburgh and its Neighbourhood,' p. 110.

[5] Quoted by Vom Rath in a paper entitled "Aus Norwegen," *Neues Jahrb.* 1869, p. 422. For another example, see Gwyn Jeffreys, *Brit. Assoc.* 1867, p. 431.

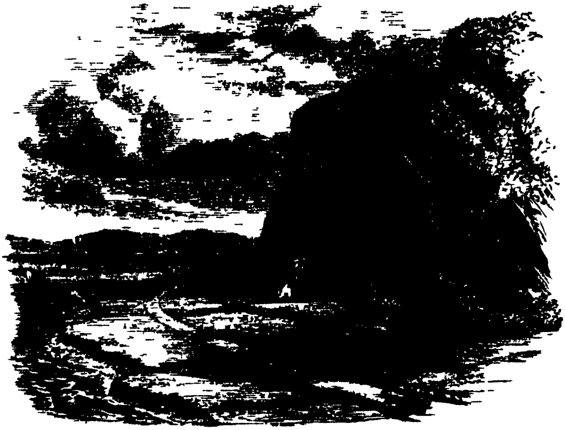

Fig. 75.—View of a line of ancient sea-cliff pierced at the base with sea-worn caves and fronted by a Raised Beach.

Raised beaches abound in the higher latitudes of the northern and southern hemispheres, and this distribution has been claimed as a strong argument in favour of the view that they are due to a fall of the local level of the sea-surface from the disappearance or diminution of former ice-caps. That some at least of the raised beaches in these regions may be due to this cause may be granted. The gradual rise of level of the beaches when traced up the fjords, which has been repeatedly asserted for some districts, would be the natural effect of the greater mass of ice in the interior. In the exploration of the lake regions of North America numerous instances have been described of a slope upward of the former water-levels towards the main ice-fields. A remarkable example is furnished by the terraces of the vanished glacial sheet of water called Lake Agassiz which once filled the basin of the Red River of the North. Mr. Warren Upham has found that these ancient lines of water-level gradually rise from south to north and from west to east, in the direction of the former ice-fields, the amount of slope ranging from zero to 1·3 feet per mile.[1] Mr. G. K. Gilbert has noticed a rise of as much as 5 feet in a mile among the old terraces of Lake Ontario.[2]

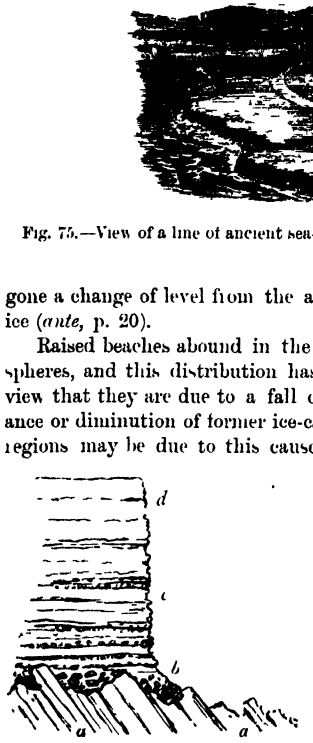

Fig. 76.—Section of a Raised Beach composed of gravel and sand (*b c*) resting on upturned slates (*a*), and passing up into blown sand (*d*) compacted by the decay of abundant land-shells. Fistrall Bay, Cornwall (*B.*)

Raised beaches occur round many parts of the coast-line of Britain. De la Beche gives the subjoined view (Fig. 77) of a Cornish locality where the existing beach is flanked by a cliff of slate, *b*, continually cut away by the sea so that the overlying raised beach, *a*, *c*, will ere long disappear. The coast line on both sides of Scotland is likewise fringed with raised beaches, sometimes four or five occurring above each other at heights of 25, 40, 50, 60, 75, and 100 feet above the present high water mark[1] Others are found on both sides of the English Channel[2] The sides of the mountainous fjords of Northern

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[1] *Bull. U. S. Geol. Surv. No.* 39 (1887), pp. 18. 20.

[2] *Science*, i. p. 222.

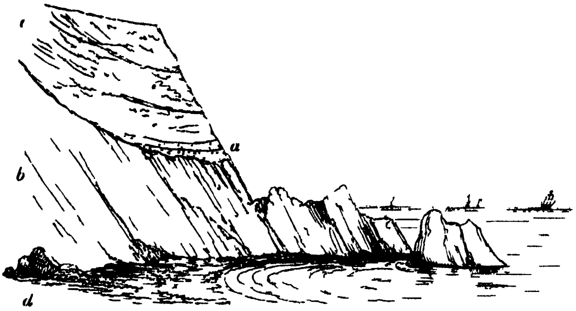

Fig 77—View of Raised Beach Nelly's Cave Cornwall (I)

Norway, up to more than 600 feet above sea level, are marked with conspicuous lines of terraces (Fig 78) These terraces are partly ordinary beach deposits, partly notches cut

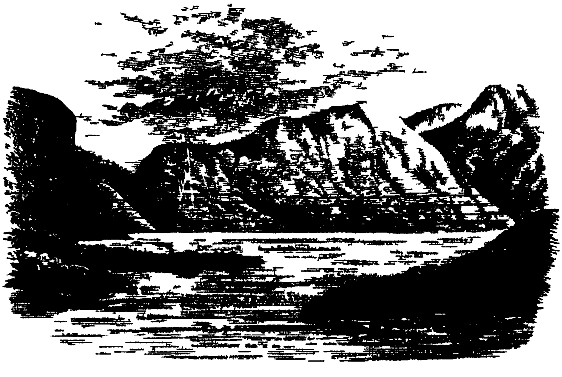

Fig 78 View of Terraces Alten Fjord Norway

out of rock, probably with the aid of drifting coast ice[3] Proofs of recent elevation of the shores of the Mediterranean are furnished by raised beaches at various heights above the present water-level. In Corsica such terraces occur at heights of from 15 to 20 metres.[1]

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[1] For accounts of some British raised beaches, see De la Beche, 'Report on Geology of Devon and Cornwall,' chap xiii C Maclaren, 'Geology of Fife and the Lothians 1839 R Chambers, 'Ancient Sea Margins,' Prestwich, *Q J Geol Soc* xxviii p 38 xxxi p 29, R Russell and T. V Holmes *Brit Assoc* 1876, Sects p 95 Ussher *Geol Mag* 1879, p 166.

[2] On the raised beach of Sangatte, near Calais, see Prestwich, *Bull Soc Geol France* (3), viii (1880), p 547, on those of Finisterre, C Barrois, *Ann Soc Geol Nord* ix (1882)

[3] See R Chambers, 'Tracings of the North of Europe' (1850), p 172 *et seq* Bravais, 'Voyages de la Commission Scientifique du Nord,' &c, translated in *Q J Geol Soc* i p 534 Kjerulf, *Z Deutsch. Geol Ges* xxii p 1, 'Die Geologie des sud und mittl Norwegen,' 1880, p 7, *Geol Mag* viii p 74 S A. Sexe, "On Rise of Land in Scandinavia,'

On the west coast of South America, lines of raised terrace containing recent shells have been traced by Darwin as proofs of a great upheaval of that part of the globe in modern geological time. The terraces are not quite horizontal but rise towards the south. On the frontier of Bolivia, they occur at from 65 to 80 feet above the existing sea-level, but nearer the higher mass of the Chilian Andes they are found at 1000, and near Valparaiso at 1300 feet. That some of these ancient sea-margins belong to the human period was shown by Mr. Darwin's discovery of shells with bones of birds, ears of maize, plaited reeds and cotton thread, in one of the terraces opposite Callao at a height of 85 feet.[2] Raised beaches occur in New Zealand, and indicate a greater change of level in the southern than in the northern part of the country.[3] It should be observed that this increased rise of the terraces polewards occurs both in the northern and southern hemispheres, and is one of the chief facts insisted upon by those who would explain the terraces by displacements of the sea rather than of the land.

Human Records and Traditions.—In countries which have been long settled by a human population, it is sometimes possible to prove, or at least to render probable, the fact of recent change of level by reference to tradition, to local names, and to works of human construction. Piers and harbours, if now found to stand above the upper limit of high-water, furnish indeed indisputable evidence of a rise of land or fall of sea-level since their erection. Numerous proofs of a recent change of level in the coast of the Arctic Ocean from Spitzbergen eastward have been observed. The Finnish coast is reported to have risen 6 feet 4 inches in 127 years.[4] At Spitzbergen itself, besides its raised beaches, bearing witness to previous elevations, small islands which existed two hundred years ago are now joined to larger portions of land. At Novaja Zemlja, where six raised beaches were found by Nordenskjold, the highest being 600 feet above sea-level,[5] there seems to have been a rising of the sea-bottom to the extent of 100 feet or more since the Dutch expedition of 1594. On the north coast of Siberia the island of Diomida, observed in 1760 by Chalaourof to the east of Cape Sviatoj, was found by Wrangel sixty years afterwards to have been united to the mainland.[6] From marks made on the coast in the middle of last century it appears that the north of Sweden has risen about 7 feet in the last 154 years, but that the movement has lessened southwards until in Scania it has been replaced by one in a downward direction (see p. 291).

§ 2. **Subsidence.**—It is more difficult to trace a downward movement of land, for the evidence of each successive sea-margin is carried down and washed away or covered up. The student will take care to guard himself against being misled by mere proofs of the advance of the sea on

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Index Scholarum of University, Christiania, 1872. H. Mohn. *Nyt. Mag. Nat.* xxii. p. 1. Dakyns, *Geol. Mag.* 1877, p. 72. K. Pettersen, *Arch. Math. Nat. Christiania*, 1878, p. 182, x. (1885); *Geol. Mag.* 1879. p. 298; *Tromso Museums Aarshefter*, III. 1880. *Sitz. Akad. Wien*, xcviii. (1889). Lehmann, 'Ueber-ehemalige Strandlinier, &c.,' Halle, 1879; *Zeitsch. ges. Naturwiss.* 1880, p. 280. A. G. Hogbom, *Geol. For. Forhandl. Stockholm*, ix. (1887), p. 19. C. Sandler, *Petermann's Mittheil.* xxxvi. (1890), pp. 209, 235.

[1] *Bull. Soc. Géol. France* (3), iv. p. 86.

[2] 'Geological Observations,' chap. ix. See *Geol. Mag.* 1877, p. 28.

[3] Haast's 'Geology of Canterbury,' 1879, p. 366.

[4] *Nature*, xxvi. p. 231.

[5] *Ibid.* xv. p. 123.

[6] Grad, *Bull. Soc. Géol. France*, 3rd ser. ii. p. 348. Traces of oscillations of level within historic times have been observed in the Netherlands, Flanders, and Upper Italy. *Bull. Soc. Géol. France*, 2nd ser. xix. p. 556; 3rd ser. ii. pp. 46, 222; *Ann. Soc. Géol. Nord.* v. p. 218. For alleged changes of level in the estuary of the Garonne, see Artigues, *Act. Soc. Linn.* Bordeaux, xxxi. (1876), p. 287, and Delfortrie, *ib.* xxxii. p. 79.

the land. In the great majority of cases, where such an advance is taking place, it is due not to subsidence of the land, but to erosion of the shores. It is, indeed, the converse of the deposition above mentioned (p. 284) as liable to be mistaken for proof of upheaval. The results of mere erosion by the sea, however, and those of actual depression of the level of the land, cannot always be distinguished without some care. The encroachment of the sea upon the land may involve the disappearance of successive fields, roads, houses, villages, and even whole parishes, without any actual change of level of the land. Certain causes, however, referred to below, may come into operation, producing an actual submergence of land without any real subsidence of the land itself. The following kinds of evidence are usually cited to prove subsidence.

Submerged Forests.—As the land is brought within reach of the waves, and its characteristic surface-features are effaced, the submerged area may retain little or no evidence of its having been a land-surface. It will be covered, as a rule, with sea-worn sand or silt. Hence, no doubt, the reason why, among the marine strata which form so much of the stratified portion of the earth's crust, and contain so many proofs of depression, actual traces of land-surfaces are comparatively rare. It is only under very favourable circumstances, as, for instance, where the area is sheltered from prevalent winds and waves, and where, therefore, the surface of the land can sink tranquilly under the sea, that fragments of that surface may be preserved under overlying marine accumulations. It is in such places that "submerged forests" occur (*Fig.* 79). These are stumps of trees still in their positions of growth in their native soil, often associated with beds of peat, full of tree-roots, hazel-nuts, branches, leaves, and other indications of a terrestrial surface. There is sometimes, however, considerable risk of deception in regard to the nature and value of such evidence of depression. Where, for instance, shingle or sand is banked up against a shore or river-mouth, considerable spaces may be enclosed and filled with fresh-water, the bottom of which may be some way below high-water mark. In such lagoons terrestrial vegetation and débris from the land may be deposited. Eventually, if the protecting barriers should be cut away the tides may flow over the layers of terrestrial peat, giving a false appearance of subsidence. Again, owing to removal of subterranean sandy deposits by springs, overlying peat-beds may sink below sea-level.

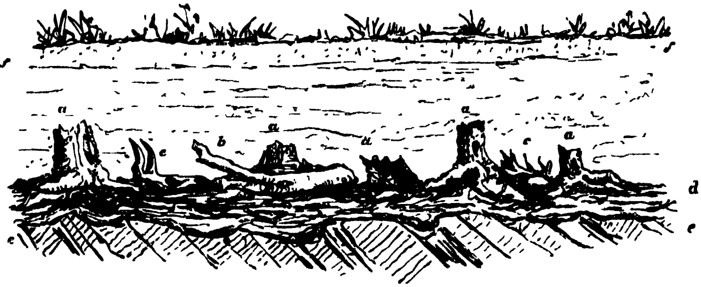

Fig. 79.—Section of Submerged Forest (*B.*)

A platform of older rocks (*e e*) has been covered with soil (*d d*) on which trees (*a a a*) have established themselves. In course of time, after some of the trees had fallen (*b*), and a quantity of vegetable soil had accumulated, enclosing here and there the bones of deer and oxen (*c c*), the area sank, and the sea overflowing it threw down upon its surface sandy or muddy deposits (*f f*).

De la Beche has described, round the shores of Devon, Cornwall, and western

Somerset, a vegetable accumulation, consisting of plants of the same species as those which now grow freely on the adjoining land, and occurring as a bed at the mouths of valleys, at the bottoms of sheltered bays, and in front of and under low tracts of land, of which the seaward side dips beneath the present level of the sea.[1] Over this submerged land-surface, sand and silt containing estuarine shells have generally been deposited, whence we may infer that, in the submergence, the valleys first became estuaries, and then sea-bays. If now, in the course of ages, a series of such submerged forests should be formed one over the other, and if, finally, they should, by upheaval of the sea-bottom, be once more laid dry, so as to be capable of examination by boring, well-sinking, or otherwise, they would prove a former long-continued depression, with intervals of rest. These intervals would be marked by the buried forests, and the progress of depression by the strata of sand and mud lying between them. In short, the evidence would be strictly on a parallel with that furnished by a succession of raised beaches as to a former protracted intermittent elevation.

Along the coasts of Holland and the north of France, submerged beds of peat have been regarded as proofs of submergence during historic times. The amount of change varies considerably in different places, and here and there can hardly be appreciated. The sinking during the 350 years preceding 1850 is estimated to have amounted in the polders of Groningen to a mean annual rate of 8 millimetres.[2] In the north of France numerous examples of submerged forests have been observed. In 1846, in digging the harbour of St. Servan, near St. Malo. a Gaulish cemetery containing ornaments and coins, and resting on a still more ancient prehistoric cemetery, was met with at a level of 6 metres below the level of high tide, so that the submergence must have been at least to that extent.[3]

Coral-islands.—Evidence of widespread depression, over the area of the Pacific and Indian Oceans, has been adduced from the structure and growth of coral-reefs and islands. Mr. Darwin, many years ago, stated his belief that, as the reef-building corals do not live at depths of more than 20 to 30 fathoms, and yet their reefs rise out of deep water, the sites on which they have formed these structures must have subsided, the rate of subsidence being so slow that the upward growth of the reefs has on the whole kept pace with it.[4] More recent researches, however, show that the phenomena of coral-reefs are in some cases, at least, capable of satisfactory explanation without subsidence, and hence that their existence can no longer be adduced by itself as a demonstration of the subsidence of large areas of the ocean.[5] The formation of coral-reefs is described in Book III. Part II. Section iii., and Mr. Darwin's theory is there more fully explained.

Distribution of plants and animals.—Since the appearance of Edward Forbes's essay upon the connection between the distribution of the existing fauna and flora of the British Isles, and the geological changes which have affected that area,[6] much attention has been given to the evidence furnished by the geographical distribution of plants and animals as to geological revolutions. In some cases, the former existence of land now submerged has been inferred with considerable confidence from the distribution of living organisms, although, as Mr. Wallace has shown in the case of the supposed "Lemuria," some of the inferences have been unfounded and unnecessary.[1] The present distribution of plants and animals is only intelligible in the light of former geological changes. As a single illustration of the kind of reasoning from present zoological groupings as to former geological subsidence, reference may be made to the fact, that while the fishes and mollusks living in the seas on the two sides of the Isthmus of Panama are on the whole very distinct, a few shells and a large number of fishes are identical; whence the inference has been drawn that though a broad water-channel originally separated North and South America in Miocene times, a series of elevations and subsidences has since occurred, the most recent submersion having lasted but a short time, allowing the passage of locomotive fishes, yet not admitting of much change in the comparatively stationary mollusks.[2]

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[1] "Geology of Devon and Cornwall," *Mem. Geol. Survey.* For further accounts of British submerged forests, see *Q. J. Geol. Soc.* xxii. p. 1. ; xxxiv. p. 447. *Geol. Mag.* vi. p. 76 ; vii. p. 64 ; iii. 2nd ser. p. 491 ; vi. pp. 80, 251. Mr. D. Pidgeon has argued in favour of the submerged forest of Torbay having been formed without subsidence of the land. *Quart. Journ. Geol. Soc.* xli. (1885), p. 9. See also W. Shone, *op. cit.* xlviii. (1892), p. 96.

[2] Lorié, *Archives du Musée Teyler,* ser. ii. vol. iii. Part 5 (1890), p. 421.

[3] Lorié, *ibid.* p. 438, and papers cited *postea,* p. 292. But see Suess, 'Antlitz der Erde,' ii. p. 547.

[4] See Darwin's 'Coral Islands,' Dana's 'Corals and Coral Islands,' and the works cited *postea,* Book III. Part II. Section iii. § 3, under "Coral-reefs" (p. 488). The various theories on the subject are discussed by R. Langenbeck in his 'Theorien über die Entstehung der Koralleninseln und Korallenriffe,' 1890.

[5] See *Proc. Roy. Phys. Soc. Edinburgh,* viii. p. 1.

[6] *Mem. Geol. Survey,* vol. i. 1846, p. 336.

Fjords.—An interesting proof of an extensive depression of the north-west of Europe is furnished by the fjords or sea-lochs by which that region is indented. A fjord is a long, narrow, and often singularly deep inlet of the sea, which terminates inland at the mouth of a glen or valley. The word is Norwegian, and in Norway fjords are characteristically developed. The English word "firth," however, is the same, and the western coasts of the British Isles furnish many excellent examples of fjords, such as the Scottish Loch Hourn, Loch Nevis, Loch Fyne, Gareloch; and the Irish Lough Foyle, Lough Swilly, Bantry Bay, Dunmanus Bay. Similar indentations abound on the west coast of British North America and of the South Island of New Zealand. Some of the Alpine lakes (Lucerne, Garda, Maggiore, and others), as well as many in Britain, are inland examples of fjords.

There can be little doubt that, though now filled with salt water, fjords have been originally land-valleys. The long inlet was first excavated as a valley or glen. The adjacent valley exactly corresponds in form and character with the hollow of the fjord, and must be regarded as merely its inland prolongation. That the glens have been excavated by subaerial agents is a conclusion borne out by a great weight of evidence, which will be detailed in later parts of this volume. If, therefore, we admit the subaerial origin of the glen, we must also grant a similar origin to its seaward prolongation. Every fjord will thus mark the site of a submerged valley. This inference is confirmed by the fact that fjords do not, as a rule, occur singly, but, like glens on land, lie in groups; so that, when found intersecting a long line of coast, such as that of the west of Norway or the west of Scotland, they show that the sea now runs far up and fills submerged glens.

Human constructions and historical records.—Should the sea be observed to rise to the level of roads and buildings which it never used to touch, should former half-tide rocks cease to be visible even at low water, and should rocks, previously above the reach of the highest tide, be turned first into shore-reefs, then into skerries and islets, we infer that the coast-line is sinking. Such kind of evidence is found in Scania, the most southerly part of Sweden. Streets, built of course above high-water mark, now lie below it, with older streets lying beneath them, so that the subsidence is of some antiquity. A stone, the position of which had been exactly determined by Linnæus in 1749, was found after 87 years to be 100 feet nearer the water's edge.[3] The west coast of Greenland, for a space of more than 600 miles, is perceptibly sinking. It has there been noticed that, over ancient buildings on low shores, as well as over entire islets, the sea has risen. The Moravian settlers have been more than once driven to shift their boat-poles inland, some of the old poles remaining visible under water.[1] Historical evidence likewise exists of the subsidence of ground in Holland and Belgium.[2] On the coast of Dalmatia, Roman roads and villas are said to be visible below the sea.[3]

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[1] 'Island Life,' 1880, p. 394. In this work the question of distribution in its geological relations is treated with admirable lucidity and fulness.

[2] A. R. Wallace, 'Geographical Distribution of Animals,' i. pp. 40, 76.

[3] According to Erdmann, the subsidence has now ceased, or has even been exchanged for an upward movement (*Geol. För. Stockholm Förhandl.* i. p. 93). Nathorst also thinks that Scania is now sharing in the general elevation of Scandinavia (*ibid.* p. 281). It appears that the zero of movement now passes through Bornholm and Laaland.

§ 3. **Causes of Upheaval and Depression of Land.**—These movements must again be traced back mainly to consequences of the internal heat of the earth. There are various ways in which this cause may have acted. As rocks expand when heated, and contract on cooling, we may suppose that, if the crust underneath a tract of land has its temperature slowly raised, as no doubt takes place round areas of nascent volcanoes, a gradual uprise of the ground above will be the result. The gradual transference of the heat to another quarter may produce a steady subsidence. Basing on the calculations of Colonel Totten, cited on p. 299, Lyell estimated that a mass of red sandstone one mile thick, having its temperature augmented 200° Fahr., would raise the overlying rocks 10 feet, and that a portion of the earth's crust of similar character 50 miles thick, with an increase of 600° or 800°, might produce an elevation of 1000 or 1500 feet.[4] But this computation, as Mr. Mellard Reade has pointed out, takes account only of linear expansion. If from any cause the mass of rock whose temperature was augmented could not expand horizontally it would rise vertically, and unless some of the surplus volume could be disposed of by condensation of the rock, the uprise would be three times as much as the linear extension. Taking this view of the case, we find that a mass of the earth's crust twenty miles thick, heated 1000° Fahr., and prevented from extending laterally, would rise 1650 feet.[5]

Again, rocks expand by fusion and contract on solidification. Hence, by the alternate melting and solidifying of subterranean masses, upheaval and depression of the surface may possibly be produced (see pp. 299, 304).

But evidently processes of this nature can only effect changes of level limited in amount and local in area. When we consider the wide tracts over which terrestrial movements are now taking place, or have occurred in past time, the explanation of them must manifestly be sought in some far more widespread and generally effective force in geological dynamics. It must be confessed, however, that no altogether satisfactory solution of the problem has yet been given, and that the subject still remains beset with many difficulties.

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[1] These observations, which have been accepted for at least a generation past (*Proc. Geol. Soc.* ii. 1835, p. 208), have recently been called in question, but the alleged disproof is not convincing, and they are here retained as worthy of credence. See Suess, *Verhand. Geol. Reichsanstalt*, 1880, No. 11, and 'Antlitz der Erde,' ii. p. 415 *et seq.*

[2] Besides the paper of Lorié, quoted on p. 290, consult Lavaleye, 'Affaissement du sol et envasement des fleuves, survenus dans les temps historiques,' Brussels, 1859. Grad, *Bull. Soc. Géol. France*, ii. 3rd ser. p. 46. Arends, 'Physische Geschichte der Nordseeküste,' 1833. Compare also R. A. Peacock on 'Physical and Historical Evidences of vast Sinkings of land on the North and West Coasts of France,' &c., London, 1868. For submerged peat-beds on French coast, see A. Gaspard, *Ann. Soc. Géol. Nord*, 1870-74, p. 40. On oscillations of French coast, T. Girard, *Bull. Soc. Géograph.* Paris, sér. 6, vol. x. p. 225; E. Delfortrie, *Act. Soc. Linn. Bordeaux*, sér. 4, vol. i. p. 79.

[3] *Boll. Com. Geol. Italiano*, 1874, p. 57.

[4] 'Principles,' ii. p. 235.

[5] Mellard Reade, 'Origin of Mountain Ranges' (1886), pp. 112, 114.

Professor Darwin, in one of his memoirs already cited (*ante*, p. 21), has suggested a possible determining cause of the larger features of the earth's surface. Assuming for his theory a certain degree of viscosity in the earth, he points out that, under the combined influence of rotation and the moon's attraction, the polar regions tend to outstrip the equator, and to acquire a consequent slow motion from west to east relatively to the equator. The amount of distortion produced by this screwing motion he finds to have been so slow, that 45,000,000 years ago, a point in lat. 30° would have been $4\frac{3}{4}'$, and a point in lat. 60° $14\frac{1}{4}'$ further west, with reference to the equator, than they are at present. This slight transference shows us, he remarks, that the amount of distortion of the surface strata from this cause must be exceedingly minute. But it is conceivable that, in earlier conditions of the planet, this screwing action of the earth may have had some influence in determining the surface features of the planet. In a body not perfectly homogeneous it might originate wrinkles at the surface running perpendicular to the direction of greatest pressure. "In the case of the earth, the wrinkles would run north and south at the equator, and would bear away to the eastward in northerly and southerly latitudes, so that at the north pole the trend would be north-east, and at the south pole north-west. Also the intensity of the wrinkling force varies as the square of the cosine of the latitude, and is thus greatest at the equator and zero at the poles. Any wrinkle, when once formed, would have a tendency to turn slightly, so as to become more nearly east and west than it was when first made."

According to the theory, the highest elevations of the earth's surface should be equatorial, and should have a general north and south trend, while in the northern hemisphere the main direction of the masses of land should bend round towards north-east, and in the opposite hemisphere towards south-east. Prof. Darwin thinks that the general facts of terrestrial geography tend to corroborate his theoretical views, though he admits that some are very unfavourable to them. In the discussion of such a theory, however, we must remember that the present mountain chains on the earth's surface are not aboriginal, but arose at many successive and widely-separated epochs. Now it is quite certain that the younger mountain-chains (and these include the loftiest on the surface of the globe) arose, or at least received their chief upheaval, during the Tertiary periods—a comparatively late date in geological history. Unless we are to enlarge enormously the limits of time which physicists are willing to concede for the evolution of the whole of that history, we can hardly suppose that the elevation of the great mountain-chains took place at an epoch at all approaching an antiquity of 45,000,000 years. Yet, according to Prof. Darwin's showing, the superficial effects of internal distortion must have been exceedingly minute during the past 45,000,000 years. We must either therefore multiply enormously the periods required for geological changes, or find some cause which could have elevated great mountain-chains at more recent intervals.

But it is well worth consideration whether the cause suggested by Prof. Darwin may not have given their initial trend to the masses of land, so that any subsequent wrinkling of the terrestrial surface, due to any other cause, would be apt to take place along the original lines. To be able to answer this question, it is necessary to ascertain the dominant line of strike of the older geological formations. But information on this subject is still scanty. In Western Europe, the prevalent line along which terrestrial plications took place during Palæozoic time was certainly from S.W. or S.S.W. to N.E. or N.N.E., and the same direction is recognisable in the eastern States of North America. But the trend of later formations is more varied. The striking contradictions between the actual direction of so many mountain-chains and masses of land, and what ought to be their line according to the theory, seem to indicate that while the effects of internal distortion may have given the first outlines to the land-areas of the globe, some other cause has been at work in later times, acting sometimes along the original lines, sometimes across them.

The main cause to which geologists are now disposed to refer the corrugations of the earth's surface is secular cooling and consequent contraction.[1] If our planet has been steadily losing heat by radiation into space, it must have progressively diminished in volume. The cooling implies contraction. According to Mallet, the diameter of the earth is less by at least 189 miles since the time when the planet was a mass of liquid.[2] But the contraction has not manifested itself uniformly over the whole surface of the planet. The crust varies much in structure, in thermal resistance, and in the position of its isogeothermal lines. As the hotter nucleus contracts more rapidly by cooling than the cooled and hardened crust, the latter must sink down by its own weight, and in so doing requires to accommodate itself to a continually diminishing diameter. The descent of the crust gives rise to enormous tangential pressures. The rocks are crushed, crumpled, and broken in many places. Subsidence must have been the general rule, but every subsidence would doubtless be accompanied with upheavals of a more limited kind. The direction of these upheaved tracts, whether determined, as Prof. Darwin suggests, by the effects of internal distortion, or by some original features in the structure of the crust, would be apt to be linear. The lines, once taken as lines of weakness or relief from the intense strain, would probably be made use of again and again at successive paroxysms or more tranquil periods of contraction. Mallet ingeniously connected these movements with the linear direction of mountain-chains, volcanic vents, and earthquake shocks. If the initial trend to the land-masses were given as hypothetically stated by Prof. Darwin, we may conceive that after the outer parts of the globe had attained a considerable rigidity and could then be only slightly influenced by internal distortion, the effects of continued secular contraction would be seen in the intermittent subsidence of the oceanic basins already existing, and in the successive crumpling and elevation of the intervening stiffened terrestrial ridges.

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[1] For an able criticism of this view see Fisher's 'Physics of Earth's Crust,' 2nd Edit. Consult also Mr. Reade's 'Origin of Mountain Ranges.'

[2] *Phil. Trans.* 1873, p. 205.

This view, variously modified, has been widely accepted by geologists as furnishing an explanation of the origin of the upheavals and subsidences of which the earth's crust contains such a long record. But it is not unattended with objections. The difficulty of conceiving that a globe possessing on the whole a rigidity equal to that of glass or steel could be corrugated as the crust of the earth has been, has led some writers to adopt the hypothesis already described (*ante*, p. 56), of an intermediate viscous layer between the solid crust and the solid nucleus, while others have suggested that the observed subsidence may have been caused, or at least aggravated, by the escape of vapours from volcanic orifices. But with modifications, the main cause of terrestrial movements is still sought in secular contraction.

Some observers, following an original suggestion of Babbage,[1] have supposed that upheaval and subsidence, together with the solidification, crystallization, and metamorphism of the layers of the earth's crust, may have been in large measure due to the deposition and removal of mineral matter on the surface. There can be no doubt that the lines of equal internal temperature (isogeothermal lines) for a considerable depth downward, follow approximately the contours of the surface, curving up and down as the surface rises into mountains or sinks into plains. The deposition of a thousand feet of rock will, of course, cause a corresponding rise in the isogeotherms, and if we assume the average rise of temperature to be 1° Fahr. for every 50 feet, then the temperature of the crust immediately below this deposited mass of rock will be raised 20°. But masses of sediment of much greater thickness have been laid down, and we may admit that a much greater increase of temperature than 20° has been effected by this means. On the other hand, the denudation of the land must lead to a depression of the isogeotherms, and a consequent cooling of the upper layers of the crust.

It may be conceded that in so far as the internal structure of rocks may be modified by such progressive increase of temperature as would arise from superficial deposit, this cause of change must have a place in geological dynamics. But it has been urged that besides this effect, the removal of rock by denudation from one area and its accumulation upon another affects the equilibrium of the crust; that the portions where denudation is active, being relieved of weight, rise, while those where deposition is prolonged, being on the contrary loaded, sink.[2] This hypothesis has recently been strongly advocated by some of the geologists who have been exploring the Western Territories of America, and who point in proof of its truth to evidence of continuous subsidence in tracts where there was prolonged deposition, and of the uprise and curvature of originally horizontal strata over mountain ranges like the Uinta Mountains in Wyoming and Utah, which have been for a long time out of water. To suppose, however, that the removal and deposit of a few thousand feet of rock should so seriously affect the equilibrium of the crust as to cause it to sink and rise in proportion, would evince such a mobility in the earth as could not fail to manifest itself in a far more powerful way under the influence of lunar and solar attraction. That there has always been the closest relation between upheaval and denudation on the one hand, and subsidence and deposition on the other, is undoubtedly true. But denudation has been one of the consequences of upheaval, and deposition has been kept up only by continual subsidence.

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[1] *Journ. Geol. Soc.* iii. (1834), p. 206.

[2] Similarly it has been contended that the accumulation of a massive ice-sheet on the land would cause a depression of the terrestrial surface. N. S. Shaler, *Proc. Boston Nat. Hist. Soc.* xvii. p. 288. T. F. Jamieson, *Quart. Journ. Geol. Soc.* 1882, and *Geol. Mag.* 1882, pp. 400, 526. Fisher, 'Physics of Earth's Crust,' p. 223.

We are concerned in the present part of this volume only with the surface features of the land in so far as they bear on questions of geological dynamics. The history of these features will be more conveniently treated in Book VII. after the structure and history of the crust have been described. Before quitting the subject, however, we may observe that the larger terrestrial features, such as the great ocean basins, the lines of submarine ridge surmounted here and there by islands chiefly of volcanic materials, the continental masses of land, and at least the cores of most great mountain chains, are in the main of high antiquity, stamped as it were from the earliest geological ages on the physiognomy of the globe, and that their present aspect has been the result not merely of original hypogene operations, but of long-continued superficial action by the epigene forces described in Book III. Part II.

Section iv. Hypogene Causes of Changes in the Texture, Structure, and Composition of Rocks.

The phenomena of hypogene action considered in the foregoing pages relate almost wholly to the effects produced at the surface. It is evident, however, that these phenomena chiefly arise from movements within or beneath the earth's crust, and must be accompanied by very considerable internal changes in the rocks which form that crust. These rocks, subjected to enormous pressure, have been contorted, crumpled, and folded back upon themselves, as if thousands of feet of solid limestones, sandstones, and shales had been merely a few layers of carpet; they have been shattered and fractured; they have in some places been pushed far above their original position, in others depressed far beneath it: so great has been the compression which they have undergone that their component particles have in many places been rearranged, and even crystallized. They have here and there probably been reduced to actual fusion, and have been abundantly invaded by masses of molten rock from below.

In the present section, the student is asked to consider chiefly the nature of the agencies by which such changes can be effected; the results achieved, in so far as they constitute part of the architecture or structure of the earth's crust, will be discussed in Book IV. At the outset, it is evident that we can hardly hope to detect many of these processes of subterranean change actually in progress and watch their effects. The very vastness of some of them places them beyond our direct reach, and we can only reason regarding them from the changes which we see them to have produced. But a good number are of a kind which can in some measure be imitated in laboratories and furnaces. It is not requisite, therefore, to speculate wholly in the dark on this subject. Since the early and classic researches of Sir James Hall, great progress has been made in the investigation of hypogene processes by experiment. The conditions of nature have been imitated as closely as possible, and varied in different ways, with the result of giving us an increasingly clear insight into the physics and chemistry of subterranean geological changes. The following pages are chiefly devoted to an illustration of the nature of hypogene action, in so far as that can be inferred from the results of actual experiment. The subject may be conveniently treated under three heads—1. The effects of mere heat; 2. the influence of the co-operation of heated water; 3. the effects of compression, tension, and fracture.

§ 1. Effects of Heat.

The importance of heat among the transformations of rocks has been fully admitted by geologists, since it used to be the watchword of the Huttonian or Vulcanist school at the end of last century. Three sources of subterranean heat may have at different times and in different degrees co-operated in the production of hypogene changes—the original internal heat of the globe, the heat arising from chemical changes within the crust or beneath it, and the heat due to the transformation of mechanical energy in the crumpling, fracturing, and crushing of the rocks of the crust.

Rise of temperature by depression.—As stated above (p. 295), the mere recession of rocks from the surface owing to superposition of newer deposits upon them will cause the isogeotherms, or lines of equal subterranean temperature, to rise—in other words, will raise the temperature of the masses so withdrawn. This can take place, however, to but a limited extent, unless combined with such depression of the crust as to admit of thick sedimentary formations. From the rate of increment of temperature downwards it is obvious that, at no great depth, the rocks must be at the temperature of boiling water, and that further down, but still at a distance which, relatively to the earth's radius, is small, they may reach and exceed the temperatures at which they would fuse at the surface. Mere descent to a great depth, however, will not necessarily result in any marked lithological change, as has been shown in the cases of the Nova Scotian and South Welsh coal-fields, where sandstones, shales, clays, and coal-seams can be proved to have been once depressed 14,000 to 17,000 feet below the sea-level, under an overlying mass of rock, and yet to have sustained no more serious alteration than the partial conversion of the coal into anthracite. They have been kept for a long period exposed to a temperature of at least 212° Fahr. Such a temperature would have been sufficient to set some degree of internal change in progress, had any appreciable quantity of water been present, whence the absence of alteration may perhaps be explicable on the supposition that these rocks were comparatively dry (p. 305).

Rise of temperature by chemical transformation.—To what extent this cause of internal heat may be operative, forms part of an obscure problem. But that the access of water from the surface, and the consequent hydration of previously anhydrous minerals must produce local augmentation of temperature, cannot be doubted. The conversion of anhydrite into gypsum, which takes place rapidly in some mines, gives rise to an increase of volume of the substance (p. 345). Besides the remarkable manner in which the rock is torn asunder by minute clefts, crystals of bitter-spar and quartz are reduced to fragments.[1] The amount of heat evolved during this process is capable of measurement. The conversion of limestone into dolomite, on the other hand, which involves a diminution of volume, might likewise be made the subject of similar experimental inquiry. Experiments with various kinds of rocks, such as clay-slate, clay, and coal, show that when these substances are reduced to powder and mixed with water, they evolve heat.[2]

Rise of temperature by rock-crushing.—A further store of heat is provided by the internal crushing of rocks during the collapse and re-adjustment of the crust. The amount of heat so produced has been made the subject of direct experiment. Daubrée has shown that, by the mutual friction of its parts, firm brick-clay can be heated in three-quarters of an hour from a temperature of 18° to one of 40° C. (65° to 104° Fahr.)[3] The most elaborate and carefully conducted series of experiments yet made in this subject are those conducted by Mallet. He subjected 16 varieties of stone (limestone, marble, porphyry, granite, and slate) in cubes averaging rather less than 1½ inches in height to pressures sufficient to crush them to fragments, and estimated the amount of pressure required, and of heat produced. The following examples may be selected from his table:[4]—

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[1] The microscopic structure of the stages in the conversion of anhydrite into gypsum is described by F. Hammerschmidt, *Tschermak's Mineral. Mittheil.* v. (1883), p. 272.

[2] W. Skey, *Chem. News*, xxx. p. 290.

[3] 'Géol. Expérimentale,' p. 448 *et seq.* This distinguished chemist and geologist has during the last forty years devoted much time to researches designed to illustrate experimentally the processes of geology. His numerous important memoirs are scattered through the *Annales des Mines*, *Comptes Rendus de l'Académie*, *Bulletin de la Société Géologique de France*, and other publications. But he has collected and republished them as 'Etudes Synthétiques de Géologie Expérimentale,' 8vo, 1879—a storehouse of information. The admirable memoirs of Delesse in the same journals should also be studied. The transformation of aragonite into calcite has been shown by Favre and Silbermann to give rise to a relatively large disengagement of heat. H. Le Chatelier, *Compt. rend.* (1893), p. 390.

[4] *Phil. Trans.* 1873, p. 187.

Rock.	Temperature (Fahr.) in 1 cubic foot of rock due to work of crushing.	Number of cubic feet of water at 32 deg. evaporated into steam at 212 deg.	Volume of ice at 32 deg. melted to water at 32 deg. by one volume of rock.
Caen Stone, Oolite	8°·004	0·0046	0·04008
Sandstone, Ayre Hill, Yorkshire	47°·79	0·0234	0·2026
Slate, Conway	132°·85	0·07	0·596
Granite, Aberdeen	155°·94	0·072	0·617
Scotch furnace-clay porphyry	198°·97	0·083	0·724
Rowley Rag (basalt)	213°·23	0·109	0·925

Within the crust of the earth, there are abundant proofs of enormous stresses under which the rocks have been crushed. The weight of rock involved in these movements has often been that of masses several miles thick. We can conceive that the heat thus generated may have been sufficient to promote many chemical and mineralogical rearrangements through the operation of water (*postea*, p. 305), and may even have been here and there enough for the actual fusion of the rocks by the crushing of which it was produced.

Rise of temperature by intrusion of erupted rock.—The great heat of lava, even when it has flowed out over the surface of the earth, has been already referred to, and some examples have been given of its effects (pp. 226, 230). Where it does not reach the surface, but is injected into subterranean rents and passages, it must effect considerable changes upon the rocks with which it comes in contact. That such intruded igneous rocks have sometimes melted down portions of the crust in their passage, can hardly be doubted. But probably still more extensive changes may take place from the exceedingly slow rate of cooling of erupted masses, and the consequently vast period during which their heat is being conveyed through the adjacent rocks. Allusion will be made in later pages to the observed amount of such "contact-metamorphism" (p. 597 *et seq*).

Expansion.—Rocks are dilated by heat. The extent to which this takes place has been measured with some precision for various kinds of rock, as shown in the subjoined table:—

Rock.	Linear expansion for every 1° Fahr.	Authority.
Black marble, Galway, Ireland	$\cdot00000247 = \frac{1}{404858}$	Adie, *Trans. Roy. Soc. Edin.* xiii. p. 366.
Grey granite, Aberdeen	$\cdot00000438 = \frac{1}{228310}$	*Ibid.*
Slate, Penrhyn, Wales	$\cdot00000576 = \frac{1}{173611}$	*Ibid.*
White marble, Sicily	$\cdot00000613 = \frac{1}{163132}$	*Ibid.*
Red sandstone, Portland, Connecticut	$\cdot00000953 = \frac{1}{104900}$	Totten, *Amer. Journ. Sci.* xxii. (1832), 136.[1]

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[1] For additional results, see Mellard Reade's 'Origin of Mountain Ranges' (1886), p. 109.

According to these data, the expansion of ordinary rocks ranges from about 2·47 to 9·63 millionths for 1° Fahr. Even ordinary daily and seasonal changes of temperature suffice to produce considerable superficial changes in rocks (see p. 328). The much higher temperatures to which rocks are exposed by subsidence within the earth's crust must have far greater effects. Some experiments by Pfaff in heating from an ordinary temperature up to a red heat, or about 1180° C., small columns of granite from the Fichtelgebirge, red porphyry from the Tyrol, and basalt from Auvergne, gave the expansion of the granite as 0·016808, of the porphyry 0·012718, of the basalt 0·01199.[1] The expansion and contraction of rocks by heating and cooling have been already referred to as possible sources of upheaval and depression (p. 292). Mr. Mellard Reade concludes from his experiments that the mean co-efficient of expansion for various classes of rocks may be taken as $\frac{1}{190192}$ for each degree Fahr., which would be equivalent to an expansion of 2·77 feet per mile for every 100° Fahr.[2]

Crystallization.—In the experiments of Sir James Hall, pounded chalk, hermetically enclosed in gun-barrels and exposed to the temperature of melting silver, was melted and partially crystallized, but still retained its carbonic acid. Chalk, similarly exposed, with the addition of a little water, was transformed to the state of marble.[3] These experiments have been repeated by G. Rose, who produced by dry heat from lithographic limestone and chalk, fine-grained marble without melting. The distinction of marble is the independent crystalline condition of its component granules of calcite. This structure, therefore, can be superinduced by heat under pressure. In nature, portions of limestone which have been invaded by intrusive masses of igneous rock, have been converted into marble, the gradations, from the unaltered into the altered rock being distinctly traceable, as will be shown in subsequent pages (p. 602).

Production of prismatic structure.—The long-continued high temperature of iron-furnaces has been observed to have superinduced a prismatic or columnar structure upon the hearth-stones, and on the sand in which these are bedded.[4] This fact is of interest in geology, seeing that sandstones and other rocks in contact with eruptive masses of igneous matter have at various depths below the surface assumed a similar internal arrangement (p. 599).

Dry fusion.—In an interesting series of experiments, the illustrious De Saussure (1779) fused some of the rocks of Switzerland and France, and inferred from them, contrary to the opinion previously expressed by Desmarest,[5] that basalt and lava have not been produced from granite, but from hornstone (pierre de corne), varieties of "schorl," calcareous clays, marls, and micaceous earths, and the cellular varieties from different kinds of slate.[6] He observed, however, that the artificial products obtained by fusion were glassy and enamel-like, and did not always recall volcanic rocks, though some exactly resembled porous lavas. Dolomieu (1788) also contended that as an artificially-fused lava becomes a glass, and not a crystalline mass with crystals of easily fusible minerals, there must be some flux present in the original lava, and he supposed that this might be sulphur.[1]

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[1] *Z. Deutsch. Geol. Ges.* xxiv. p. 403.

[2] 'Origin of Mountain Ranges,' p. 110.

[3] *Trans. Roy. Soc. Edin.* vi. (1805), pp. 101, 121. See note on next page.

[4] C. Cochrane, *Proc. Dudley Geol. Soc.* iii. p. 54.

[5] *Mém. Acad. Scien.* 1771, p. 273.

[6] De Saussure, 'Voyages dans les Alpes,' edit. 1803, tome i. p. 178.

Sir James Hall, about the year 1790, began an important investigation, in which he succeeded in reducing various ancient and modern volcanic rocks to the condition of glass, and in restoring them, by slow cooling, to a stony condition in which distinct crystals (probably pyroxene, olivine, and perhaps enstatite) were recognisable.[2] Gregory Watt afterwards obtained similar results by fusing much larger quantities of the rocks. In more recent years, this method of research has been resumed and pursued with the much more effective appliances of modern science, notably by Mitscherlich, G. Rose, C. Sainte-Claire Deville, Delesse, Daubrée, Fouqué, Michel-Lévy, Friedel, and Sarasin. It has been experimentally proved that all rocks undergo molecular changes when exposed to high temperature, that when the heat is sufficiently raised, they become fluid, that if the glass thus obtained is rapidly cooled it remains vitreous, and that, if allowed to cool slowly, a more or less distinct crystallization sets in, the glass is devitrified, and a lithoid product is the result.

A glass is an amorphous substance resulting from fusion, perfectly isotropic in its action on transmitted polarized light (*ante*, pp. 114, 120). Its specific gravity is rather lower than that of the same substance in the crystallized condition. By being allowed to cool slowly, or being kept for some hours at a heat which softens it, glass assumes a dull porcelain-like aspect. This devitrification possesses much interest to the geologist, seeing that most volcanic rocks, as has been already described (p. 120), present the characters of devitrified glasses. It consists in the appearance of minute crystallites, and other imperfect or rudimentary crystalline forms, accompanied with an increase of density and diminution of volume. It must be regarded as an intermediate stage between the perfectly glassy and the crystalline conditions. Rocks exposed to temperatures as high as their melting-points fuse into glass which, in the great majority of cases, is of a bottle-green or black colour, the depth of the tint depending mainly on the proportion of iron. In this respect they resemble the natural glasses—pitchstones and obsidians. Microscopic investigation of such artificially-fused rocks shows that, even in what seems to be a tolerably homogeneous glass, there are abundant minute hair-like, feathered, needle-shaped, or irregularly-aggregated bodies diffused through the glassy paste. These crystallites, in some cases colourless, in others opaque, metallic oxides, particularly oxides of iron, resemble the crystallites observed in many volcanic rocks (p. 115). They may be obtained even from the fusion of a granitic or granitoid rock, as in the well-known case of the

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[1] 'Iles Ponces,' p. 8 *et seq.* At temperatures between 2000° and 3000° C., various metallic oxides are fused and crystallize. H. Moissan, *Compt. rend.* cxv. (1892), p. 1034.

[2] *Trans. Roy. Soc. Edin.* v. p. 43. Hall's actual products have been microscopically examined by Fouqué and Michel-Lévy. *Comptes rend.* May 1881. For repetitions of his fusion of limestone, *op. cit.* cxv. (1892), pp. 817, 934, 1009, 1296.

Mount Sorrel syenite near Leicester, which, being fused and slowly cooled, yielded to Mr. Sorby abundant crystallites, including exquisitely-grouped octohedra of magnetite.[1]

According to the observations of Delesse, volcanic rocks, when reduced to a molten condition, attack briskly the sides of the Hessian crucibles in which they are contained, and even eat them through. This is an interesting fact, for it helps to explain how some intrusive igneous rocks have come to occupy positions previously filled by sedimentary strata, and why, under such circumstances, the composition of the same mass of rock should be found to vary considerably from place to place.[2]

The most elaborate and successful experiments yet made regarding the fusion of igneous rocks, are those of MM. Fouqué and Michel-Lévy. These observers, by mixing the chemical elements and, in other cases, the mineralogical constituents, of certain minerals and rocks, and fusing these in platinum crucibles in a gas-furnace, have been able to produce both rock-forming minerals, such as several felspars, augite, leucite, nepheline, and garnet, and also rocks possessing the composition and microscopic structure of augite-andesites, leucite-tephrites, and true basalts. By rapid cooling, they obtained an isotropic glass, often full of bubbles, and varying in colour with the nature of the mixture from which it was formed. Where the mixture contains the elements of pyroxene, enstatite, or melilite, it must be cooled very rapidly to prevent these minerals from partially crystallizing out of the glass. Nepheline also crystallizes easily. The felspars, on the other hand, pass much more slowly from the viscous to the crystalline condition. In these experiments, use was made of the law that the fusion-temperature of a crystallized silicate is usually higher than that of the same substance in the glassy state. Hence if such a glass be kept sufficiently long at a temperature slightly higher than that at which it softens, the most favourable conditions are obtained for the production of molecular arrangements and the formation of those crystalline bodies which can solidify in the midst of a viscous magma. The limits of temperature for the production of a given mineral must thus be comprised within the narrow range between the fusion-point of the mineral and that of its glass. By varying the temperature in the experiments, distinct minerals can be obtained from the same magma. Minerals such as olivine, leucite, and felspar, which solidify at higher temperatures than the others, appear first, and the later forms are moulded round them. Thus an artificial basalt, like a natural one, always shows that its olivine has crystallized first. By providing facilities for the crystallization of the minerals in the inverse order of their fusibilities, the characters of naturally formed crystalline rocks can thus be artificially produced by simple igneous fusion.

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[1] Zirkel, *Mik. Besch.* p. 92; Sorby, *Address Geol. Sect. Brit. Assoc.* 1880. On the microscopic structure of slags, &c., see Vogelsang's 'Krystalliten.'

[2] *Bull. Soc. Géol. France*, 2nd ser. iv. 1382; see also *Trans. Edin. Roy. Soc.* xxix. p. 492. In the more recent experiments by Doelter and Hussak no change was observed in the porcelain crucibles in which basalt, andesite and phonolite were melted. *Neues Jahrb.* 1884, p. 19. Bischof has described a series of experiments on the fusion of lavas with different proportions of clay-slate. He found that the lava of Niedermendig, kept an hour in a bellows-furnace, was reduced to a black glassy substance without pores, and that a similar product was obtained even after 30 per cent of clay-slate had been added and the whole had been kept for two hours in the furnace. 'Chem. und Phys. Geol.' supp. (1871), p. 98.

Certain well-known facts which appear to militate against the principle of these experiments have been successfully explained by MM. Fouqué and Michel-Lévy. Some minerals, very difficult to fuse, contain crystals of others which are easily fusible, as if the latter had crystallized first, as in the case of pyroxene enclosed within leucite. But in reality the pyroxene has slowly crystallized out of inclusions of the surrounding glass which were caught up in the leucite. Where the same silicates are found to have crystallized first in large and subsequently in smaller forms, they may reveal stages in the gradual cooling and consolidation of the mass, one set of crystals, for example, being formed in a lava while still within the vent of a volcano, and another during the more rapid cooling after expulsion from the vent.

The rocks obtained artificially by these observers are thus classed by them:—1. Andesites and andesitic porphyrites—from the fusion of a mixture of four parts of oligoclase and one of augite. 2. Labradorites and labradoric porphyrites—from the fusion of three parts of labrador and one of augite. 3. A microlitic rock formed of pyroxene and anorthite. 4. Basalts and labradoric melaphyres—from the fusion of a mixture of six parts of olivine, two of augite and six of labrador. 5. Nephelinites—from the fusion of a mixture of three parts of nepheline and 1·3 of augite. 6. Leucitites—from the fusion of nine parts of leucite and one of augite. 7. Leucite-tephrite—from the fusion of a mixture of silica, alumina, potash, soda, magnesia, lime, and oxide of iron, representing one part of augite, four of labrador, and eight of leucite. 8. Lherzolite. 9. Meteorites without felspar. 10. Meteorites with felspar. 11. Diabases and dolerites with ophitic structure. In these artificially produced compounds the most complete resemblance to natural rocks was observed, down even to the minutiæ of microscopic structure. The crystals and microlites ranged themselves exactly as in natural rocks, with the same distribution of vitreous base and vitreous inclusions. It is thus demonstrated that a rock like basalt may be produced in nature in the dry way, by a process entirely igneous.[1]

More recently, another series of experiments has been carried on by Messrs. Doelter and Hussak of Gratz, to determine the effect of immersing various minerals in molten basalt, andesite, or phonolite. Among the results obtained by them are the production of a granular structure in pyroxene and hornblende, especially along the borders, as may be observed in the hornblende of recent eruptive rocks; the conversion of a hornblende crystal, which still retains its form, into an aggregate of augite prisms and magnetite, as observed also in some basalts; the conversion of garnet into various other minerals, such as meionite, melilite, anorthite, lime-olivine, lime-nepheline, specular iron, and spinel, the garnet itself never reappearing in the molten magma.[1]

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[1] See the work of Messrs Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches,' 1882, from which the above digest of their researches is taken. Since this was written I have had the advantage of being shown by M. Michel-Lévy the original slides prepared from the products obtained by him and M. Fouqué, and I can entirely corroborate the results at which these observers have arrived. They have succeeded in imitating all the essential features of such rocks as basalt, down even into minute microscopic details. They have produced rocks, not only showing microlitic forms, but with crystals of the constituent minerals as definitely formed as in any natural lava. Indeed it would be hardly possible to distinguish between one of their artificial products and many true lavas.

While experiment has thus shown that certain eruptive rocks of the basic order, such as basalts and augite-andesites, may be produced by mere dry fusion, the acid rocks present difficulties which have as yet proved insuperable in the laboratory. MM. Fouqué and Michel-Lévy have vainly endeavoured to reproduce by igneous fusion rocks with quartz, orthoclase, white mica, black mica, and amphibole. We may therefore infer that these rocks have been produced in some other way than by dry igneous fusion. The acid rocks, terminating in granite, form a remarkable series, regarding the origin of which we are still completely ignorant. Some data relating to their production will be given in § 2 (p. 308) in connection with the co-operation of underground water.

Contraction of rocks in passing from a glassy to a stony state.—Reference has been made (pp. 56, 292, 299) to the expansion of rocks by heat and their contraction on cooling; likewise to the difference between their volume in the molten and in the solid state. It would appear that the diminution in density, as rocks pass from a crystalline into a vitreous condition, is, on the whole, greater the more silica and alkali are present, and is less as the proportion of iron, lime, and alumina increases. According to Delesse, granites, quartziferous porphyries, and such highly silicated rocks lose from 8 to 11 per cent of their density when they are reduced to the condition of glass, basalts lose from 3 to 5 per cent, and lavas, including the vitreous varieties, from 0 to 4 per cent.[2] More recently, Mallet observed that plate-glass (taken as representative of acid or siliceous rocks) in passing from the liquid condition into solid glass contracts 1·59 per cent, 100 parts of the molten liquid measuring 98·41 when solidified; while iron-slag (having a composition not unlike that of many basic igneous rocks) contracts 6·7 per cent, 100 parts of the molten mass measuring 93·3 when cold.[3] By the contraction due to such changes in the internal condition of subterranean masses of rock, minor oscillations of level of the surface may be accounted for, as already stated (p. 292). Thus, the vitreous solidification of a molten mass of siliceous rock 1000 feet thick might cause a subsidence of about 16 feet, while, if the rock were basic, the amount of subsidence might be 67 feet.

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[1] *Neues Jahrb.* 1884, pp. 18, 158. Compare also A. Becker's experiments in melting pyroxenes and amphiboles, *Zeitsch. Deutsch. Geol. Gesell.* xxxvii. (1885), p. 10.

[2] *Bull. Soc. Géol. France*, 1847, p. 1390. Bischof had determined the contraction of granite to be as much as 25 per cent (Leonhard und Bronn, *Jahrb.* 1841). The correctness of this determination was disputed by D. Forbes (*Geol. Mag.* 1870, p. 1), who found from his own experiments that the amount of contraction must be much less. The values given by him were still much in excess of those afterwards obtained with much care by Mallet. Compare O. Fisher, 'Physics of the Earth's Crust,' 2nd Edit., p. 45, and Barus quoted *ante*, p. 56.

[3] *Phil. Trans.* clxiii. pp. 201, 204; clxv.; *Proc. Roy. Soc.* xxii. p. 328.

Sublimation.—It has long been known that many mineral substances can be obtained in a crystalline form from the condensation of vapours (pp. 196, 228). This process, called Sublimation, may be the result of the mere cooling and reappearance of bodies which have been vaporised by heat and solidify on cooling, or of the solution of these bodies in other vapours or gases, or of the reaction of different vapours upon each other. These operations, of such common occurrence at volcanic vents, and in the crevices of recently erupted and still hot lava-streams, have been successfully imitated by experiment. In the early researches of Sir James Hall on the effects of heat modified by compression, he obtained by sublimation "transparent and well-defined crystals," lining the unoccupied portion of a hermetically-sealed iron tube, in which he had placed and exposed to a high temperature some fragments of limestone.[1] Numerous experiments have been made by Delesse, Daubrée, and others in the production of minerals by sublimation. Thus, many of the metallic sulphides found in mineral veins have been produced by exposing to a comparatively low temperature (between that of boiling water and a dull-red heat) tubes containing metallic chlorides and sulphide of hydrogen. By varying the materials employed, corundum, quartz, apatite, and other minerals have been obtained. It is not difficult, therefore, to understand how, in the crevices of lava-streams and volcanic cones, as well as in mineral veins, sulphides and oxides of iron and other minerals may have been formed by the ascent of heated vapours. Superheated steam is endowed with a remarkable power of dissolving that intractable substance, silica; artificially heated to the temperature of the melting-point of cast-iron, it rapidly attacks silica, and deposits the mineral in snow-white crystals as it cools. Sublimation, however, can hardly be conceived as having operated in the formation of rocks, save here and there in the infilling of open fissures.

§ 2. Influence of Heated Water.

In the geological contest fought at the beginning of the century between the Neptunists and the Plutonists, the two great battle-cries were, on the one side, Water, on the other, Fire. The progress of science since that time has shown that each of the parties had some truth on its side, and had seized one aspect of the problems touching the origin of rocks. If subterranean heat has played a large part in the construction of the materials of the earth's crust, water, on the other hand, has performed a hardly less important share of the task. They have often cooperated together, and in such a way that the results must be regarded as their joint achievement, wherein the respective share of each can hardly be exactly apportioned. In Part II. of this Book the chemical operation of infiltrating water, at ordinary temperatures at the surface, and among rocks at limited depths, is described. We are here concerned mainly with the work done by water when within the influence of subterranean heat, and the manner in which this work can be experimentally imitated.

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[1] *Trans. Roy. Soc. Edin.* vi. p. 110.

Presence of water in all rocks.—Besides its combinations in hydrous minerals, water may exist in rocks either (1) retained interstitially among minute crevices and pores, or (2) imprisoned within the microscopic cells of crystals.

(1.) By numerous observations it has been proved that all rocks within the accessible portion of the earth's crust contain interstitial water, or, as it is sometimes called, quarry-water (*eau de carrière*). This is not chemically combined with their mineral constituents, but is merely retained in their pores. Most of it evaporates when the stone is taken out of the parent rock, and freely exposed to the atmosphere. The absorbent powers of rocks vary greatly, and chiefly in proportion to their degree of porosity. Gypsum absorbs from about 0·50 to 1·50 per cent of water by weight; granite, about 0·37 per cent; quartz from a vein in granite, 0·08; chalk, about 20·0; plastic clay, from 19·5 to 24·5. These amounts may be increased by exhausting the air from the specimens and then immersing them in water.[1] No mineral substance is strictly impervious to the passage of water. The well-known artificial colouring of agates proves that even mineral substances, apparently the most homogeneous and impervious, can be traversed by liquids. In the series of experiments above referred to (p. 266), Daubrée has illustrated the power possessed by water of penetrating rocks, in virtue of their porosity and capillarity, even against a considerable counter-pressure of vapour; and, without denying the presence of original water, he concludes that the interstitial water of igneous rocks may all have been derived by descent from the surface. The masterly researches of Poiseuille have shown that the rate of flow of liquids through capillaries is augmented by heat. He proved that water at a temperature of 45° C. in such situations moves nearly three times faster than at a temperature of 0° C.[2] At the high temperatures under which the water must exist at some depth within the crust, its power of penetrating the capillary interstices of rocks must be increased to such a degree as to enable it to become a powerful geological agent.

(2.) Reference has already (p. 110) been made to the presence of minute cavities, containing water and various solutions, in the crystals of many rocks. The water thus imprisoned was obviously enclosed with its gases and saline solutions, at the time when these minerals crystallized out of their parent magma. The quartz of granite is usually full of such water-vesicles. "A thousand millions," says Mr. J. Clifton Ward, "might easily be contained within a cubic inch of quartz, and sometimes the contained water must make up at least 5 per cent of the whole volume of the containing quartz."

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[1] See an interesting paper by Delesse, *Bull. Soc. Géol. France*, 2me sér. xix. (1861-2), p. 65.

[2] *Comptes Rendus* (1840), xi. p. 1048. Pfaff ('Allgemeine Geologie,' p. 141) concludes from calculations as to the relations between pressure and tension that water may descend to any depth in fissures and remain in a fluid state even at high temperatures.

Solvent power of water among rocks.—The presence of interstitial water must affect the chemical constitution of rocks. It is now well understood that there is probably no terrestrial substance which, under proper conditions, is not to some extent soluble in water. By an interesting series of experiments, made many years ago by W. B. and H. D. Rogers, it was ascertained that the ordinary mineral constituents of rocks could be dissolved to an appreciable extent even by distilled water, and that the change was accelerated and augmented by the presence of carbonic acid.[1] Water, as pure as it ever occurs in a natural state, can hold in solution appreciable proportions of silica, alkaliferous silicates, and iron oxide, even at ordinary temperatures. The mere presence, therefore, of water within the pores of subterranean rocks cannot but give rise to changes in the composition of these rocks. Some of the soluble materials must be dissolved, and, as the water evaporates, will be redeposited in a new form.[2]

This power increased by heat.—The chemical action of water is increased by heat, which may be either the earth's original heat or that which arises from internal crushing of the crust. Mere descent from the surface into successive isogeotherms raises the temperature of permeating water until it may greatly exceed the boiling-point. But a high temperature is not necessary for many important mineral rearrangements. Daubrée has proved that very moderate heat, not more than 50° C. (122° Fahr.) has sufficed for the production of zeolites in Roman bricks by the mineral waters of Plombières.[3] He has experimentally demonstrated the vast increase of chemical activity of water with augmentation of its temperature, by exposing a glass tube containing about half its weight of water to a temperature of about 400° C. At the end of a week he found the tube so entirely changed into a white, opaque, powdery mass, as to present not the least resemblance to glass. The remaining water was highly charged with an alkaline silicate containing 63 per cent of soda and 37 per cent of silica, with traces of potash and lime. The white solid substance was ascertained to be composed almost entirely of crystalline materials, partly in the form of minute perfectly limpid bipyramidal crystals of quartz, but chiefly of very small acicular prisms of wollastonite. It was found, moreover, that the portion of the tube which had not been directly in contact with the water was as much altered as the rest, whence it was inferred that, at these high temperatures and pressures, the vapour of water acts chemically like the water itself.

Co-operation of pressure.—The effect of pressure must be recognised as most important in enabling water, especially when heated, to dissolve and retain in solution a larger quantity of mineral matter than it could otherwise do,[4] and also in preventing chemical changes which take place at once when the pressure is removed.[5] In Daubrée's experiments above cited, the tubes were hermetically sealed and secured against fracture, so that the pressure of the greatly superheated vapour had full effect. By this means, with alkaline water, he not only produced the two minerals above mentioned, but also felspar and diopside. The high pressures under which many crystalline rocks have solidified is indicated by the liquid carbon-dioxide in the vesicles of their crystals. Besides the pressure due to their varying depth from the surface, they must have been subject to the enormous expansion of the superheated water or vapour which filled all their cavities, and sometimes, also, to the compression resulting from the secular contraction of the globe and consequent corrugation of the crust. Mr. Sorby inferred that in many cases the pressure under which granite consolidated must have been equal to that of an overlying mass of rock 50,000 feet, or more than 9 miles in thickness, while De la Vallée Poussin and Renard from other data deduced a pressure equal to 87 atmospheres (p. 112).

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[1] *American Journ. Science* (2), v. p. 401.

[2] See further on this subject, *postea*, pp. 343, 364. [3] 'Géologie Expérimentale,' p. 462.

[4] Sorby has shown that the solubility of all salts which exhibit contraction in solution is remarkably increased by pressure. *Proc. Roy. Soc.* (1862-3), p. 340.

[5] See Cailletet, *Naturforscher*, v.; Pfaff, *Neues Jahrb.* 1871; W. Spring, *Bull. Acad.*

Aquo-igneous fusion.—As far back as the year 1846, Scheerer observed that there exist in granite various minerals which could not have consolidated save at a comparatively low temperature.[1] He instanced especially gadolinites, orthites, and allanites, which cannot endure a higher temperature than a dull-red heat without altering their physical characters; and he concluded that granite, though it may have possessed a high temperature, cannot have solidified from simple igneous fusion, but must have been a kind of pasty mass containing a considerable proportion of water. It is common now to speak of the "aquo-igneous" origin of some eruptive rocks, and to treat their production as a part of what are termed the "hydro-thermal" operations of geology.

Scheerer, Élie de Beaumont, and Daubrée have shown how the presence of a comparatively small quantity of water in eruptive igneous rocks may have contributed to suspend their solidification, and to promote the crystallization of their silicates at temperatures considerably below the point of fusion and in a succession different from their relative order of fusibility. In this way, the solidification of quartz in granite after the crystallization of the silicates, which would be unintelligible on the supposition of mere dry fusion, becomes explicable. The water may be regarded as a kind of mother-liquor out of which the silicates crystallize without reference to relative fusibility.

The researches of the late Professor Guthrie on the influence of water in lowering the fusing points of various substances have an important geological bearing. He showed that while the melting-point of nitre by itself is 320° C., an admixture of only 1·14 per cent of water reduced the temperature of fusion by 20°, while by increasing the proportion of water to 29·07 per cent he lowered the melting-point to 97·6°, and he concluded that "the phenomenon of fusion is nothing more than an extreme case of liquefaction by solution." He could see no reason why water should not exist even at the earth's centre, for even granting that

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Roy. Belgique, 2nd Ser. xlix. (1880), p. 369. Pfaff found that plaster does not absorb water under a pressure of 40 atmospheres.

[1] *Bull. Soc. Géol. France*, iv. p. 468.

it has a "critical temperature," still, "at high pressures it will be compressible as a vapour to a density at least as great as that of liquid water." He concluded that "water at a high temperature may not only play the part of a solvent in the ordinary restricted sense, but that there is in many cases no limit to its solvent faculty; in other words, that it may be mixable with certain rocks in all proportions; that solution and mixture are continuous with one another, in some cases at temperatures not above the temperature of fusion of those bodies *per se*."[1]

Professor Guthrie was disposed to doubt whether the replenishment of water by capillary descent from the surface was necessary for the production of these phenomena of fusion and volcanic eruption. Prof. Daubrée's experiments, however, enable us to see how the supply of water may be kept up from superficial sources, while from those of Prof. Guthrie we learn that when the descending water reaches masses of highly-heated but still solid rock, it may allow them to pass into a fused condition and to exert a powerful expansive force on the overlying crust.

Artificial production of minerals.—As the result of experiments, both in the dry and moist way, various minerals have been produced in the crystalline form. Among the minerals successfully reproduced are quartz, tridymite, olivine, pyroxene, enstatite, wollastonite, zircon, emerald, ruby, melanite, melilite, several felspars, leucite, nepheline, meionite, petalite, several zeolites, dioptase, rutile, brookite, anatase, perowskite, sphene, calcite, aragonite, dolomite, witherite, siderite, cerusite, malachite, corundum, diaspore, spinel, hæmatite, vivianite, apatite, anhydrite, diamond with many metallic ores.[2]

Artificial alteration of internal structures.—Besides showing the solvent power of superheated water and vapour upon glass in illustration of what happens within the crust of the earth, Daubrée's experiments possess a high interest and suggestiveness in regard to the internal rearrangements and new structures which water may superinduce upon rocks. Hermetically sealed glass tubes containing scarcely one-third of their weight of water, and exposed for several days to a temperature below an incipient red heat, showed not only a thorough transformation of structure into a white, porous, kaolin-like substance, encrusted with innumerable bipyramidal crystals of quartz, like those of the drusy cavities of rocks, but had acquired a very distinct fibrous and even an eminently schistose structure. The glass was found to split readily into concentric laminæ arranged in a general way parallel to the original surfaces of the tube, and so thin that ten of them could be counted in a breadth of a single millimetre. Even where the glass, though attacked, retained its vitreous character, these fine zones appeared like the lines of an agate. The whole structure recalled that of some schistose and crystalline rocks. Treated with acid, the altered glass crumbled and permitted the isolation of certain nearly opaque globules and of some minute transparent infusible acicular crystals or microlites, sometimes grouped in bundles and reacting on polarized light. Reduced to thin slices and examined under the microscope with a magnifying power of 300 diameters, the altered glass presented: 1st, Spherulites, $\frac{5}{10}$ of a millimetre in radius, nearly opaque, yellowish, bristling with points which perhaps belong to a kind of crystallization, and with an internal radiating fibrous structure (these resist the action of concentrated hydrochloric acid, whence they cannot be a zeolite, but may be a substance like chalcedony); 2nd, innumerable colourless acicular microlites, with a frequently stellate, more rarely solitary distribution, resisting the action of acid like quartz or an anhydrous silicate; 3rd, dark green crystals of pyroxene (diopside). Daubrée satisfied himself that these enclosures did not pre-exist in the glass, but were developed in it during the process of alteration.[1]

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[1] *Phil. Mag.* xviii. (1884), p. 117.

[2] Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches.'

But beside the effects from increase of temperature and pressure, we have to take into account the fact that water in a natural state is never chemically pure. Rain, falling through the air, absorbs in particular oxygen and carbon-dioxide, and filtering through the soil, abstracts more of this oxide as well as other results of decomposing organic matter. It is thus enabled to effect numerous decompositions of subterranean rocks, even at ordinary temperatures and pressures. But as it continues its underground journey, and obtains increased solvent power, the very solutions it takes up augment its capacity for effecting mineral transformations. The influence of dissolved alkaline carbonates in promoting the decomposition of many minerals was long ago pointed out by Bischof. In 1857 Sterry Hunt showed by experiments that water impregnated with these carbonates would, at a temperature of not more than 212° Fahr., produce chemical reactions among the elements of many sedimentary rocks, dissolving silica and generating various silicates.[2] Daubrée likewise proved that in presence of dissolved alkaline silicates, at temperatures above 700° Fahr. various siliceous minerals, as quartz, felspar, and pyroxene, could be crystallized, and that at this temperature the silicates would combine with kaolin to form felspar.[3]

The presence of fluorine has been proved experimentally to have a remarkable action in facilitating some precipitates, especially tin oxides, as well as in other parts of the mechanism of mineral veins.[4] Further illustrations of the important part probably played by this element in the crystallization of some minerals and rocks have been published by Ste. Claire Deville and Hautefeuille, who by the use of compounds of fluorine have obtained such minerals as rutile, brookite, anatase and corundum in crystalline form.[5] Élie de Beaumont inferred that the mineralizing influence of fluorine had been effective even in the crystallization of granite. He believed that "the volatile compound enclosed in granite, before its consolidation contained not only water, chlorine, and sulphur, like the substance disengaged from cooling lavas, but also fluorine, phosphorus and boron, whence it acquired much greater activity and a capacity for acting on many bodies on which the volatile matter contained in the lavas of Etna has but a comparatively insignificant action."[1]

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[1] 'Géol. Expérim.' p. 158 *et seq.* The production of crystals and microlites in the devitrification of glass at comparatively low temperatures by the action of water is of great interest. The first observer who described the phenomenon appears to have been Brewster, who, in the second decade of this century, studied the effect upon polarized light of glass decomposed by ordinary meteoric action. (*Phil. Trans.* 1814, *Trans. Roy. Soc. Edin.* xxii. (1860), p. 607. See on the weathering of rocks, p. 345.)

[2] *Phil. Mag.* xv. p. 68.

[3] *Bull. Soc. Géol. France*, xv. (1885), p. 103.

[4] First suggested by Daubrée, *Ann. des Mines* (1841), 3me sér. xx. p. 65.

[5] *Comptes Rendus*, xlvi. p. 764 (1858); xlvii. p. 89; lvii. p. 648 (1865). Fouqué and Michel-Lévy, 'Synthèse des Minéraux et des Roches.'

§ 3. Effects of compression, tension, and fracture.

Among the geological revolutions to which the crust of the earth has been subjected, its rocks have been in some places powerfully compressed; elsewhere they have undergone enormous tension, and almost everywhere they have been more or less ruptured. Hence internal structures have been developed which were not originally present in the rocks. These structures will be more properly considered in Book IV. We are here concerned mainly with the nature and operation of the agencies by which they have been produced.

The most obvious result of pressure upon rocks is consolidation, as where a mass of loose sand is gradually compacted into a more or less coherent stone, or where, with accompanying chemical changes, a layer of vegetation is compressed into peat, lignite, or coal. The cohesion of a sedimentary rock may be due merely to the pressure of the superincumbent strata, but some cementing material has usually contributed to bind the component particles together. Of these natural cements the most frequent are peroxide of iron, silica, and carbonate of lime. Moderate pressure equally distributed over a rock presenting everywhere nearly the same amount of resistance will promote consolidation, but may produce no further internal change. Where the component particles are chiefly crystalline, pressure may induce a crystalline structure upon the whole mass, as recent experiments have shown.[2] If, however, the pressure becomes extremely unequal, or if the rock subjected to it can find escape from the strain in one or more directions, it may undergo shear in certain planes, or may be crumpled, or the limit of its rigidity may be passed, and rupture may take place. Some consequences of these movements may be briefly alluded to here in illustration of hypogene action in dynamical geology.

(1.) **Minor Ruptures and Noises.**—Among mountain-valleys, in railway-tunnels through hilly regions, or elsewhere among rocks subjected to much lateral pressure, or where owing to the removal of material by running water, and the consequent formation of cavities, subsidence is in progress, sounds as of explosions are occasionally heard. In many instances, these noises are the result of relief from great lateral compression, the rocks having for ages been in a state of strain, from which as denudation advances, or as artificial excavations are made, they are relieved. This relief takes place, not always uniformly, but sometimes cumulatively by successive shocks or snaps. Mr. W. H. Niles of Boston has described a number of interesting cases where the effects of such expansion could be seen in quarries; large blocks of rock being rent and crushed into fragments, and smaller pieces being even discharged with explosion into the air.[1] More recently Mr. A. Strahan has called attention to the occurrence of slickensided surfaces in the lead-mines of Derbyshire which on being struck or even scratched with a miner's pick break off with explosive violence, and he suggests that the spars and ores along those surfaces are in "a state of molecular strain, resembling that of the Rupert's Drop or of toughened glass, and that this condition of strain is the result of the earth movements which produced the slickensides."[2]

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[1] "Sur les Emanations Volcaniques et Métallifères," *Bull. Soc. Géol. France*, iv. (1846), p. 1249. This admirable and exhaustive memoir, one of the greatest monuments of Élie de Beaumont's genius, should be consulted by the student. See also De Lapparent (*Bull. Soc. Géol. France*, xvii. (1889), p. 282) on the part played by mineralizing agents in the formation of eruptive rocks.

[2] W. Spring, *Bull. Acad. Roy. Belg.* 1880, p. 375.

If such is the state of strain in which some rocks exist even at the surface or at no great distance beneath it, we can realise that at great depths, where escape from strain is for long periods impossible, and the compression of the masses must be enormous, any sudden relief from this strain may well give rise to an earthquake-shock (p. 280). A continued condition of strain must also influence the solvent power of water permeating the rocks (p. 307).

(2.) **Consolidation and Welding.**—That pressure consolidates rocks is familiar knowledge. Loose sedimentary materials may by mere pressure be converted into more or less firm and hard masses. Experiments by W. Spring upon many substances in the state of powder have shown that under high pressure they become welded into solid substances. Under a pressure of 6000 atmospheres, coal-dust becomes a brilliant solid block, taking the mould of the cavity in which it is placed, and thereby giving evidence of plasticity. Peat, in like manner, becomes a brilliant black substance in which all trace of the original structure is gone.[3]

(3.) **Cleavage.**—Over extensive tracts of country a peculiar structure has been superinduced by powerful lateral pressure, especially upon fine-grained argillaceous rocks, which are then termed slates. They split along a set of planes which, as a rule, are highly inclined or vertical, and independent of the original bedding. Examined more minutely, it is found that their component particles, which in most cases have a longer and shorter axis, have grouped themselves with their long axes generally in one common direction, and parallel with the planes of fissility. An ordinary shale may present under the microscope such a structure as is shown in Fig. 81. But where it has undergone the change here referred to, it has acquired the structure represented in Fig. 80. Rocks which, having been thus acted on, have acquired this superinduced fissility, are said to be cleaved, and the fissile structure is termed cleavage. In Fig. 82, for example, where the strata, at first in even parallel beds, have been subjected to great compression from the directions (A) and (B), the original planes of stratification are represented by wavy lines, and the new system

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[1] *Proc. Boston Soc. Nat. Hist.* xviii. p. 272 (1876).

[2] *Geol. Mag.* 1887, p. 400. See also the same volume, pp. 511, 522.

[3] *Bull. Acad. Roy. Belg.* 1880, p. 325, and *ante*, p. 142.

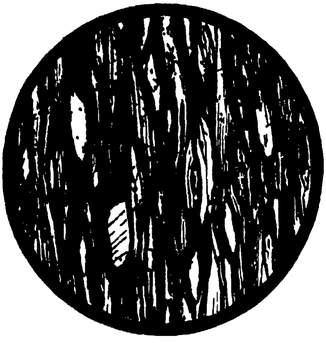

Fig. 80.—Section of compressed argillaceous rock in which cleavage-structure has been developed. Magnified. (Compare Fig 256.)

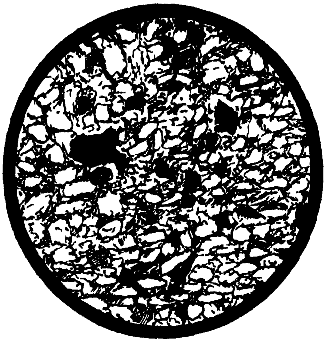

Fig. 81.—Section of a similar rock which has not undergone this modification. Magnified.

of cleavage-planes by fine upright lines. The fineness of the cleavage depends in large measure upon the texture of the original rock. Sandstones, consisting as they do of rounded obdurate quartz-grains, take either a very rude cleavage (or jointing) or none at all. Fine-grained argillaceous rocks, consisting of minute particles or flakes, that can adjust their long axes in a new direction, are those in which the structure is best developed. In a series of cleaved rocks, therefore, cleavage may be perfect in argillaceous beds (*b b*, Figs. 83 and 84), and imperfect or absent

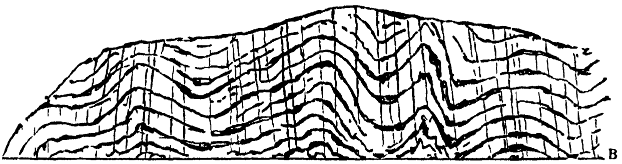

Fig 82.—Curved quartz-rock traversed by vertical and highly-inclined Cleavage. South Stack Lighthouse, Anglesea (*B.*)

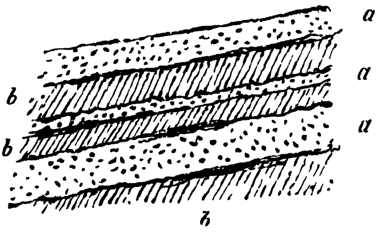

Fig. 83.

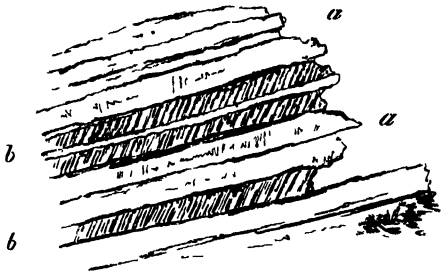

Fig. 84.

Dependence of Cleavage upon the grain of the rock (*B.*)

in interstratified beds of sandstone (*a a*, Fig. 83) or of limestone (as at Clonea Castle, Waterford, *a a*, Fig. 84).

That cleavage may be produced in a mechanical way by lateral pressure has been proved experimentally by Sorby, who effected perfect cleavage in pipe-clay through which scales of oxide of iron had previously been mixed.[1] Tyndall superinduced cleavage on bees-wax and other substances by subjecting them to severe pressure. More recently, Fisher has proposed the view that in nature it is not to the pressure which plicated the rocks that cleavage is to be attributed, but to the shearing movements generated in large masses of rock left in a position too lofty for equilibrium.[2] If such, however, had been the origin of the structure, it is difficult to understand why there should be such a prevalent relation between the strike and the cleavage; for if descent by gravitation were the main cause, we should expect to find the rocks sheared far more irregularly than even the most irregular disposition of cleavage. That in cleavage there has been a true distortion of the rocks is indubitable; and the amount of distortion may be ascertained by the extent of the alteration of shape of fossils (Figs. 85-88). Microscopic study of cleaved rocks shows that their fissility is not always due merely to a rearrangement of original clastic particles, but to the development of new minerals, particularly varieties of mica, along the planes of cleavage. This relation is well seen in the folded and cleaved Devonian and Carboniferous rocks of S.W. Ireland and Cornwall, in the Carboniferous shales of Laval, Mayenne, and in the Jurassic and Eocene shales of the Alps.[3] Just as shales graduate into true cleaved slates, so slates by augmentation of their superinduced mica pass into phyllites, and these into mica-schists. The structure of districts with cleaved rocks is described in Book IV. Part V.

(4.) **Deformation.**—Further evidence of the powerful pressures to which rocks have been exposed is furnished by the way in which contiguous pebbles in a conglomerate have been squeezed into each other, and even sometimes have been elongated in a certain general direction. The coarseness of the grain of such rocks permits the effects of compression or tension to be readily seen. Similar effects may take place in fine-grained rocks and escape observation. Daubrée has imitated experimentally indentations produced by the contiguous portions of conglomerate pebbles.[4]

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[1] Hopkins, *Cambridge Phil. Trans.* viii. (1847), p. 456. D. Sharpe, *Quart. Journ. Geol. Soc.* iii. (1846), p. 74; v. (1848), p. 111. Sorby, *Edin. New Phil. Journ.* lv. (1853), p. 137. W. King, *Roy. Irish Acad.* xxv. (1875), p. 605. The student will find recent interesting additions to our knowledge of the microscopic structure and the history of cleaved rocks in Mr. Sorby's address, *Q. J. Geol. Soc.* xxxvi. p. 72, and in Mr. Harker's very able essay, *Brit. Assoc.* 1885, Reports, pp. 813-852. See also E. Jannettaz, *Bull. Soc. Géol. France*, ix. (1881), p. 196; xi. (1884), p. 211. G. F. Becker, *Bull. Geol. Soc. Amer.* iv. (1893), p. 13.

[2] *Geol. Mag.* 1884, p. 396.

[3] Jannettaz, Renevier and Lory, *Bull. Soc. Géol. France*, ix. p. 649.

[4] *Comptes Rendus*, xliv. p. 823; also his 'Géologie Expérimentale,' part i. sect. ii. chap. iii., where a series of important experiments on deformation is given. For various examples and opinions, see Rothpletz, *Z. Deutsch. Geol. Ges.* xxxi. p. 355. Heim, 'Mechanismus der

In discussing the cause of these indentations it must be remembered that imprints of pebbles upon each other, particularly when the material is limestone or other tolerably soluble rock, may have been to some extent produced by solution taking place most actively where pressure was greatest (p. 307). But there are indubitable evidences of crushing and deformation, even in what would be termed solid and brittle rocks. Of these evidences, perhaps the most instructive and valuable are furnished by the remains of plants and animals occurring as fossils, and of which the unaltered shapes are well known. Where fossiliferous rocks have undergone a shear, the extent of this movement, as above remarked, can be measured in the resultant distortion of the fossils. In Figs. 85 and 87 drawings are given of two Lower Silurian fossils in their natural forms.

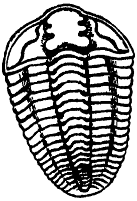
Fig. 85.—A Trilobite (*Calymene Blumenbachii*), natural shape.

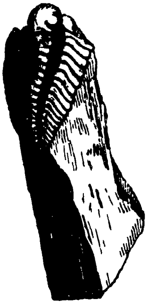
Fig. 86.—The same Trilobite, altered by deformation—Lower Silurian, Hendre Wen, near Cerig y Druidion, North Wales (*B.*)

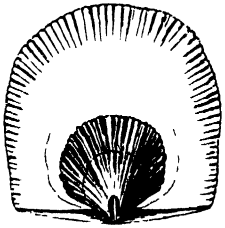
Fig. 87.—A Brachipod (*Strophomena expansa*), natural shape.

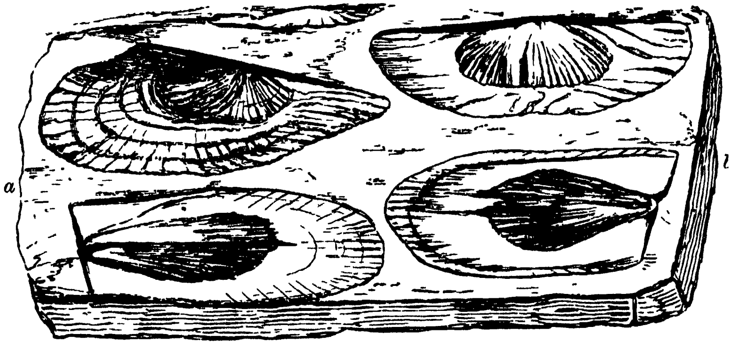

Fig. 88.—*Strophomena expansa*, altered by the deforming influence of Cleavage—Lower Silurian, Cwm Idwal, Caernarvonshire (*B*)

Gebirgsbildung,' 1878, vol. ii. p. 31. Hitchcock, 'Geology of Vermont,' i. p. 28. *Proc. Bost. Soc. Nat. Hist.* vii. pp. 209, 353 ; xviii. p. 97 ; xv. p. 1 ; xx. p. 313. *Amer. Assoc.* 1866, p. 83. *Amer. Jour. Sci.* (2) xxxi. p. 372. Sorby, *Rep. Cardiff Nat. Soc.* 1873, p. 21. H. H. Reusch, 'Fossilien-führender Kryst. Schiefer,' p. 25.

In Fig. 86 a specimen of the same species of trilobite as in Fig. 85 is represented where it has been distorted during the shearing of the enclosing rock. In Fig. 88 four examples of the same shell as in Fig. 87 are shown greatly distorted by a strain which has elongated the rock in the direction *a b*.[1] Amorphous crystalline rocks (pegmatite, granite, diorite) have been so crushed as to acquire a schistose structure (pp. 544, 545, 597, 615, 625, 630).

Another illustration of the effects of pressure in producing deformation in rocks, is supplied by the so-called "lignilites," "epsomites," or "stylolites." These are cylindrical or columnar bodies varying in length up to more than four inches, and in diameter up to two or more inches. The sides are longitudinally striated or grooved. Each column, usually with a conical or rounded cap of clay, beneath which a shell or other organism may frequently be detected, is placed at right angles to the bedding of the limestones, or calcareous shales through which it passes, and consists of the same material. This structure has been referred by Professor Marsh to the difference between the resistance offered by the column under the shell, and by the surrounding matrix to superincumbent pressure. The striated surface in this view is a case of "slickensides." The same observer has suggested that the more complex structure known as "cone-in-cone" may be due to the action of pressure upon concretions in the course of formation.[2]

The ingenious experiments of M. Tresca[3] on the flow of solids have thrown considerable light upon the internal deformations of rock-masses. He has proved that, even at ordinary atmospheric temperatures, solid resisting bodies like lead, cast-iron, and ice, may be so compressed as to undergo an internal motion of their parts, closely analogous to that of fluids. Thus, a solid jet of lead has been produced, by placing a piece of the metal in a cavity between the jaws of a powerful compressing machine. Iron, in like manner, has been forced to flow in the solid state into cavities and take their shape. On cutting sections of the metals so compressed, their particles or crystals are found to have ranged themselves in lines of flow which follow the contour of the space into which they have been squeezed. Such experiments are of considerable geological interest. They illustrate how in certain circumstances, under great strain, rocks may not only be made to undergo internal deformation along certain shearing planes, as in cleavage, but may even be subjected to such stresses as to acquire a "shear-structure" resembling the fluxion-structure seen in rocks which have been truly liquid (p. 544).[4]

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[1] See D. Sharpe, *Q. J. Geol. Soc.* iii. (1846), p. 75. W. Hopkins, *Cambridge Phil. Trans.* viii. (1847), p. 466. S. Haughton, *Phil. Mag.* (1856), xii. p. 409. O. Fisher, *Geol. Mag.* 1884, p. 399. Harker, *Brit. Assoc.* 1885, Reports, p. 824.

[2] *Proc. American Assoc. Science*, 1867. Gumbel, *Zeitsch. Deutsch. Geol. Ges.* xxxiv. p. 642.

[3] *Comptes Rendus*, 1864, p. 754 ; 1867, p. 809. *Mém. Sav. Étrangers*, xviii. p. 733 ; xx. p. 75. *Inst. Mech. Engineers*, June 1867 ; June 1878. See also W. C. Roberts-Austen, *Proc. Roy. Institution*, xi. (1886), p. 395.

[4] This remarkable kind of structure has been developed to an enormous extent among the crystalline rocks of the north-west Highlands of Scotland (p. 624).

Numerous examples have been found during the last few years in the north-west Highlands of Scotland where rocks have been subjected to such mechanical movements as to have been crushed down and made to flow in certain directions. Massive crystalline pegmatites may there be traced through successive stages until the material becomes a fine compact felsitic substance with thin lines of flow so like the "flow-structure" of a lava that it would deceive even a practised geologist, and sometimes splitting into thin laminæ like those of shale. Further reference to this subject will be made in Book IV. Part VIII. § 2.

(5.) **Plication.**—On the assumption of a more rapid contraction of the inner hot nucleus of the globe, and the consequent descent of the cool upper shell, a subsiding area of the curved surface of the earth requires to occupy less horizontal space, and must therefore suffer powerful lateral compression. De la Beche long ago pointed out that if contorted and tilted beds were levelled out, they would require more space than can now be obtained for them without encroaching on other areas.[1] The magnificent example of the Alps brings before the mind the enormous extent to which the crust of the earth has in some places been compressed. According to the measurements and estimates of Professor Heim of Zurich, the diameter of the northern zone of the central Alps is only about one half of the original horizontal extent of the component strata, which have been corrugated and thrown back upon each other in huge folds reaching from base to summit of lofty mountains, and spreading over many square miles of surface. He computes the horizontal compression of the whole chain at 120,000 mètres, that is to say, that two points on the opposite sides of the chain have, by the folding of the crust that produced the Alps, been brought 120,000 mètres, or 74 miles, nearer each other than they were before the movement.[2] Though the sight of such colossal foldings of solid sheets of rock impresses us with the magnitude of the compression to which the crust of the earth has been subjected, it perhaps does not convey a more vivid picture of the extent of this compression than is afforded by the fact that even in the minuter and microscopic structure of the rocks intricate puckerings are visible (Fig. 37). So intense has been the pressure, that even the tiny flakes of mica and other minerals have been forced to arrange themselves in complex, frilled, crimped, and goffered foldings. On an inferior scale, local compression and contortion may be caused by the protrusion of eruptive rocks. The characters of plicated rocks as part of the framework of the terrestrial crust are given in Book IV. Part IV.

As may be supposed, it is difficult to illustrate experimentally the processes by which vast masses of rock have been plicated and crumpled The early devices of Sir James Hall, however, may be cited from their interest as the first attempts to demonstrate the origin of the contortion of rocks. He placed layers of cloth under a weight, and by compressing them from two sides produced corrugations closely resembling those of the Silurian strata of the Berwickshire coast (Fig. 89). Professor Favre of Geneva devised an experiment which more closely imitates the conditions in nature. Upon a tightly stretched band of india-rubber he places various layers of clay, making them adhere to it as firmly as possible. By then allowing the band to contract he produces in the overlying strata of clay a series of contortions, inversions, and dislocations which at once recall those of a great mountain-chain.[1] More recently this subject has been illustrated experimentally by Mr. H. M. Cadell, who has obtained results curiously like those exhibited by the crumpled and dislocated rocks of the N.W. Highlands of Scotland.[2]

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[1] 'Report, Devon and Cornwall,' p. 187.

[2] 'Mechanismus der Gebirgsbildung,' 1878, vol. ii. p. 213.

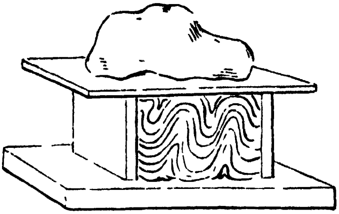

Fig. 69.—Hall's Experiment illustrating contortion.

(6.) **Jointing and Dislocation.**—Almost all rocks are traversed by vertical or highly inclined divisional planes termed *joints* (Book IV. Part II.) These have been regarded as due in some way to contraction during consolidation (fissures of retreat); and this is no doubt their origin in innumerable cases. But, on the other hand, their frequent regularity and persistence across materials of very varying texture suggest rather the effects of internal pressure and movement within the crust. In an ingenious series of experiments, Daubrée has imitated joints and fractures by subjecting different substances to undulatory movement by torsion and by simple pressure, and he infers that they have been produced by analogous movements in the terrestrial crust.[3]

But in many cases the rupture of continuity has been attended with relative displacement of the sides, producing what is termed a *fault.* Daubrée also shows experimentally how faults may arise from the same movements as have caused joints, and from bending of the rocks. As the solid crust settles down, the subsidence, where unequal in rate, may cause a rupture between the less stable and more stable areas. When a tract of ground has been elevated, the rocks underlying it get more room by being pushed up, and are placed in a position of more or less instability. As they cannot occupy the additional space by any elastic expansion of their mass, they accommodate themselves to the new position by a series of dislocations.[4] Those segments having a broad base rise more than those with narrow bottoms, or the latter sink relatively to the former. Each broad-bottomed segment is thus bounded by two sides sloping towards the upper part of the block. The plane of dislocation is nearly always inclined from the vertical, and the side to which the inclination rises, and from which it "hades," is the upthrow side. Faults of this kind are termed *normal,* and are by far the most common in nature. In mountainous regions, however, instances frequently occur where one side has been pushed over the other, so that lower are placed above higher beds. Such a fault is said to be *reversed.* It indicates an upward thrust within the crust, and is often to be found associated with lines of plication. Where a sharp fold, of which one limb is pushed forward over the other, gives way along a line of rupture, the result is a reversed fault. The details of these features of geological structure are reserved for Book IV. Part VI.

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[1] *Nature,* xiv. (1878), p. 103.

[2] *Trans. Roy. Soc. Edin.* xxxvi. (1888), p. 337.

[3] 'Géol. Expérim.' Part I. sect. ii. chap. ii. See W. King, *Roy. Irish Acad.* xxv. (1875), p. 605, and the theories of jointing given *postea,* p. 526.

[4] See J. M. Wilson, *Geol. Mag.* v. p. 206; O. Fisher, *op. cit.* 1884.

§ 4. The Metamorphism of Rocks.

Metamorphism is a crystalline (usually also a chemical) rearrangement of the constituent materials of a rock.[1] In its production the following conditions have been mainly operative. (1) Temperature, from the lowest at which any change is possible up to that of complete fusion; (2) pressure, the potency of the action of heat being, within certain limits, increased with increase of pressure; (3) mechanical movements, which so often have induced molecular rearrangements in rocks; (4) presence of water, usually containing various mineral solutions, whereby chemical changes would be effected which would not be possible in dry heat; (5) nature of the materials operated upon, some being much more susceptible of change than others.

A metamorphosed rock is one which has suffered such a mineralogical rearrangement of its substance. It may or may not have been a crystalline rock originally. Any rock capable of alteration (and all rocks must be so in some degree) will, when subjected to the required conditions, be metamorphosed. The resulting structure, however, will, save in extreme cases, bear witness to the original character of the mass. In some instances, the change has consisted merely in the rearrangement or crystallization of one mineral originally present, as in limestone converted into marble; in others, there has been a process of paramorphism, as where augite has been changed into hornblende in the alteration of dolerites into epidiorites; in others, the constituents have been forced by mechanical movements to range themselves in parallel laminæ, as where a diorite or pyroxenic rock becomes a hornblende-schist; in others, partial or complete transformation of the original constituents, whether crystalline or clastic, into new crystalline minerals has been accompanied by a complete recrystallization and change of structure in the rock. Quartzite is evidently a compacted sandstone, either hardened by mere pressure, or most frequently by the deposit of silica between its granules, or a slight solution of these granules by permeating water, so that they have become mutually adherent. A clay-slate is a hardened, cleaved, and partially metamorphosed form of muddy sediment, which on the one hand may be found full of organic remains, like any common shale, while on the other, by the appearance and gradual increase of some form of mica and other minerals, it may be traced becoming more and more crystalline, until it passes into phyllite, chiastolite-slate, or some other schistose rock. Yet remains of fossils may be obtained even in the same hand-specimens with crystals of andalusite, garnet, or other minerals. The calcareous matter of corals is sometimes replaced by hornblende, garnet, and axinite, without deformation of the fossils.[1]

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[1] See A. Harker on the Physics of Metamorphism, *Geol. Mag.* vi. (1889), p. 15. J. W. Judd, *ib.* p. 243, and Book IV. Part VIII. of this Text-book.

Since experiment has proved that in presence of water under pressure, even at comparatively low temperatures, mineral substances are vigorously attacked (p. 307), we may expect to find that as these conditions abundantly exist within the earth's crust, the rocks exposed to them have been more or less altered. A large proportion of the accessible crust consists of sedimentary materials which were laid down on the ocean-bottom, and which were still abundantly soaked with sea-water even after they had been covered over with more recent formations. The gradual growth of submarine accumulations would of course deprive the lower strata of most of their original water, but some proportion of it would probably remain. If, according to Dana, the average amount of interstitial water in stratified rocks, at the earth's surface, such as limestones, sandstones and shales, be assumed to be 2·67 per cent, which is probably less than the truth, "the amount will correspond to two quarts of water for every cubic foot of rock."[2] There is certainly a considerable store of water ready for chemical action when the required conditions of heat and pressure are obtained. We must also remember that the water in which the sedimentary formations of the crust were formed, being mostly that of the ocean, already possessed chlorides, sulphates, and other salts with which to begin its reactions. The inference may therefore be drawn, that rocks possessing not more than 3 per cent of interstitial water cannot be depressed to depths of several thousand feet beneath the level of the earth's surface, and undergo great pressure and crushing, without suffering more or less marked internal change or metamorphism.

A few illustrative examples of metamorphism may be given here; the structure of metamorphic rocks, with the phenomena of "contact" and "regional" metamorphism, will be discussed in Book IV. Part VIII.

Production of marble from limestone.—One of the most obvious cases of alteration—the artificial conversion of limestone into crystalline saccharoid marble—has been already referred to (p. 300).[3] The calcite having undergone complete transformation, its original structure, whether organic or not, has been effaced, and a new structure has been developed, consisting of an aggregate of minute rounded grains, each with an independent crystalline arrangement. The production of a crystalline structure in amorphous calcite may be effected by the action of mere meteoric water at or near the surface (*ante*, p. 151, and *postea*, p. 365). But the generation of the peculiar granular structure of marble always demands heat and pressure, and probably usually the presence of water; the details of the process are, however, still involved in obscurity. We know that where a dyke of basalt or other intrusive rock has involved limestone, it has sometimes been able to convert it for a short distance into marble. The heat (and perhaps the moisture) of the invading lava have sufficed to produce a granular structure, which even under the microscope is identical with that of marble. The conversion of wide areas of limestone into marble is a regional metamorphism, associated usually with the alteration of other sedimentary masses into schists, &c.

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[1] *Ann. des Mines*, 5me sér. xii. p. 318. H. H. Reusch, 'Die Fossilien führenden krystallinischen Schiefer von Bergen' (translated by R. Baldauf), Leipzig, 1883.

[2] 'Manual,' 3rd ed. (1880), p. 758.

[3] See also "Marmarosis" in Book IV. Part VIII.

Dolomitization.—Another alteration which, from the labours of Von Buch, received in the early decades of this century much attention from geologists, is the conversion of ordinary limestone into dolomite. Some dolomite appears to be an original chemical precipitate from the saline water of inland lakes and seas (p. 412). But calcareous formations due to organic secretions are often weakly dolomitic at the time of their formation, and may have their proportion of magnesium carbonate increased by the action of permeating water, as is proved by the conversion into dolomite of shells and other organisms, consisting originally of calcite or aragonite, and forming portions of what was no doubt originally a limestone, though now a continuous mass of dolomite. This change may have sometimes consisted in the mere abstraction of carbonate of lime from a limestone already containing carbonate of magnesia, so as to leave the rock in the form of dolomite; or probably more usually in the action of the magnesium salts of sea-water, especially the chloride, upon organically-formed limestone; or sometimes locally in the action of a solution of carbonate of magnesia in carbonated water upon limestone, either magnesian or non-magnesian. Élie de Beaumont calculated that on the assumption that one out of every two equivalents of carbonate of lime was replaced by carbonate of magnesia, the conversion of limestone into dolomite would be attended with a reduction of the volume of the mass to the extent of 12·1 per cent. It is certainly remarkable in this connection that large masses of dolomite, which may be conceived to have once been limestone, have the cavernous, fissured structure which, on this theory of their origin, might have been looked for.

Dolomite has been produced both on a small and on a great scale. In the north of England and elsewhere, the Carboniferous Limestone has been altered for a few feet or yards on either side of its joints into a dull yellow dolomite, locally termed "dunstone." Similar vertical zones of dolomite occur also in the Carboniferous Limestone of Ireland. Harkness pointed out that the dolomite appears in vertical ribs where the rocks are much jointed, and in beds where they have few or no joints.[1] No doubt percolating water has been the agent of change in the vertical zones. The beds, however, which in Ireland and elsewhere constitute important masses in the Carboniferous Limestone, were more probably formed contemporaneously with the rocks among which they lie. They may have been deposited as limestone in shallow lagoons where the magnesian salts of concentrated sea-water would act upon them. Dolomite sometimes forms great ranges of mountains, as in the Eastern Alps, where it has by some writers been regarded as altered ordinary limestone. But these masses, may have partly, at least, become dolomite at the beginning by the action of the magnesian salts of the concentrated waters of inland seas upon organic or inorganic calcareous deposits accumulated previous to the concentration, their metamorphism having consisted mainly in the subsequent generation of a crystalline structure analogous to that of the conversion of limestone into marble.[1]

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[1] *Q. J. Geol. Soc.* xv. p. 100.

Conversion of vegetable substance into coal.—Exposed to the atmosphere, dead vegetation is decomposed into humus, which goes to increase the soil. But sheltered from the atmosphere, exposed to the action of water, especially with an increase of temperature, and under some pressure, it is converted into lignite and coal. An example of this alteration has been observed in the Dorothea mine, Clausthal. Some of the timber in a long-disused level, filled with slate rubbish, and saturated with the mine-water from decomposing pyrites, was found to have a leathery consistence when wet, but, on exposure to the air, hardened to a firm and ordinary brown-coal, with the typical brown colour and external fibrous structure, and having the internal fracture of a black glossy pitch-coal.[2] This change must have been produced within less than four centuries—the time since the levels were opened. According to Bischof's determinations the conversion of wood into coal may take place, 1st, by the separation of carbonic acid and carburetted hydrogen; 2nd, by the separation of carbonic acid, and the formation of water either from oxidation of hydrogen by meteoric oxygen, or from the hydrogen and oxygen of the wood; 3rd, by the separation of carbonic acid, carburetted hydrogen, and water.[3] The circumstances under which the vegetable matter now forming coal has been accumulated were favourable for this slow transmutation. The carbon-dioxide (choke-damp) of old coal-mines and the carburetted hydrogen (fire-damp, CH_4) given off in such large quantities by coal seams, are products of the alteration which would appear to be accelerated by terrestrial movements, such as those that compress and plicate rocks. During the process these gases escape, and the proportion of carbon progressively increases in the residue, till it reaches the most highly mineralised anthracite (p. 144), or may even pass into nearly pure carbon or graphite. In the coal-basins of Mons and Valenciennes, the same seams which are in the state of bituminous coal (*gras*) at the surface, gradually lose their volatile constituents as they are traced downward till they pass into anthracite. In the Pennsylvanian coal-field the coals become more anthracitic as they are followed into the eastern region, where the rocks have undergone great plication, and where, possibly during the subterranean movements, they were exposed to an elevation of temperature.[1] Daubrée has produced from wood, exposed to the action of superheated water, drop-like globules of anthracite which had evidently been melted in the transformation, and which presented a close resemblance to the anthracite of some mineral veins.[2]

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[1] On dolomitization, see L. von Buch, in Leonhard's *Mineralog. Taschenbuch*, 1824; Naumann's 'Geognosie,' i. p. 763; Bischof's 'Chemical Geology,' iii.; Élie de Beaumont, *Bull. Soc. Géol. France*, viii. (1836), p. 174; Sorby, *Brit. Assoc. Rep.* 1856, part ii. p. 77, and *Address*, *Q. J. Geol. Soc.* 1879. A full statement of the literature of this subject will be found in a suggestive memoir by C. Doelter and R. Hoernes, *Jahrb. Geol. Reichsanstalt*, xxv. The dolomite mountains of the Eastern Alps have been well described by Mojsisovics. See account of Triassic system, *postea*, Book VI.

[2] Hirschwald, *Z. Deutsch. Geol. Ges.* xxv. p. 364.

[3] Bischof, 'Chem. Geol.' i. p. 274.

Production of New Minerals.—Where metamorphism is well developed the chemical reactions which have been set up have given rise to more or less complete re-combination of the chemical constituents of the rock. New minerals have thus been formed either entirely out of the materials already comprising the rock, or with some addition or replacement of substance introduced from without, by aqueous solution or otherwise. Some of the commonest secondary minerals are micas; andalusite, chiastolite, and garnet are also of frequent occurrence. (See Book IV. Part VIII.)

Production of the schistose structure.—All rocks are not equally permeable by water, nor is the same rock equally permeable in all directions. Among the stratified rocks especially, which form so large a proportion of the visible terrestrial crust, there are great differences in the facility with which water can travel, the planes of sedimentation, or those of cleavage or shearing where these have been developed, being naturally those along which water passes most easily. It is along these planes that differences of mineral structure and composition are ranged. Alternate layers of siliceous, argillaceous, and calcareous material vary in porosity and capability of being changed by permeating water. We may, therefore, expect that unless the original stratified structure has been effaced or rendered inoperative by any other superinduced structure, it will guide the metamorphic action of underground water, and will remain more or less distinctly traceable even after very considerable mineralogical transformations have taken place. Even without this guiding influence, superheated water can, to a certain extent, produce a schistose structure, parallel to its bounding surfaces, as Daubrée's experiments upon glass, above cited, have proved.

The stratified formations consist largely of silica, silicates of alumina, lime, magnesia, soda and potash, and iron oxides. These mineral substances exist there as original ingredients, partly in recognisable worn crystals, partly in a granular or amorphous condition, ready to be acted on by permeating water under the requisite conditions of temperature and pressure. We can understand that any re-combination and re-crystallization of the silicates will probably follow the laminæ of deposit or of cleavage, and that in this way a crystalline foliated structure may be developed. Round masses of granite erupted among Palæozoic rocks, instructive sections may be observed where a transition can be traced from ordinary unaltered sedimentary strata, such as sandstones, greywackes and shales containing fossils, into foliated crystalline rocks, to which the names of mica-schist and even gneiss may be applied. (Book

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[1] Daubrée, 'Géologie Expérimentale,' p. 463. Part of the framework below a steam-hammer has been found after twenty years to be converted into lignite. F. Seeland, *Verh. Geol. Reichs.* 1883, p. 192.

[2] *Op. cit.* p. 177.

IV. Part VIII.) Not only can the gradual change into a crystalline foliated structure be readily followed with the naked eye, but with the aid of the microscope the finer details of the alteration can be traced. Minute plates of some micaceous mineral and small concretions of andalusite, garnet, quartz, &c., may be observed to have crystallized out of the surrounding amorphous sediment. These, especially the mica, can be seen gradually to increase in size and number towards the granite, until the rock assumes a thoroughly foliated structure and passes into a true schist. Yet even in such a schist, traces of the original and durable water-worn quartz-granules may be detected.[1] Foliation is a crystalline segregation of the mineral matter of a rock in certain dominant planes which may be those of original stratification, of joints, of cleavage, of shearing, or of fracture.[2] Mr. Sorby has recognised foliation in three sets of planes even among the same rocks.[3]

Scrope many years ago called attention to the analogy between the foliation of schists and the ribbanded or streaked structure of trachyte, obsidian, and other lavas.[4] This analogy has even been regarded as an identity of structure, and the idea has found supporters that the schistose rocks have been in a condition similar to or identical with that of many volcanic masses, and have acquired their peculiar fissility by differential movements within the viscous or pasty magma, the solidified minerals being drawn out into layers in the direction of shearing. Daubrée, availing himself of the researches of Tresca on the flow of solids (p. 316), has endeavoured to imitate artificially some of the phenomena of foliation by exposing clay and other substances to great but unequal pressure.[5] That some of the lenticular wavy laminæ of different minerals in gneiss and other foliated rocks may be due to original segregation or flow in still unconsolidated igneous rock seems to be rendered highly probable by the curious analogies to this structure to be observed in the deeper parts of large intrusive bosses of rock, such as granite, diabase, and gabbro. These layers may thus be the remains of the oldest structure now retained by the gneiss. But subsequent pressure and deformation have frequently produced a foliation cutting obliquely across this original lamination and even entirely effacing it.

That the schistose structure has been largely induced by mechanical movements cannot be doubted. The evidence in the field and under the microscope has now rendered it certain that many rocks have been subjected to enormous mechanical stresses within the earth's crust; that they have yielded to the pressure both by disruption and by molecular shearing, that in some cases they have been crushed into minute fragments or dust, and have then been made to flow and to simulate the flow-structure of lava, while, in other cases, the crushed particles have crystallized into a granulitic structure, or the recrystallization has taken place along the flow-planes and has given rise to a perfect foliation. The action that produced cleavage, if further developed, might be accompanied with sufficient augmentation of temperature to permit of extensive mineralogical transformation along the cleavage-planes. But probably a rise of temperature was not essential. The conversion of pyroxene into hornblende, which has been observed in regions of crystalline schists, points indeed to a lower temperature than that required for the crystallization of the original mineral.[1] A schistose structure of almost any degree of coarseness might conceivably be produced. A mixed rock, such as granite, has been converted into a foliated gneiss. Diorite, diabase, or gabbro has likewise by mechanical movement, with accompanying chemical and crystallographic transformation, been made to assume a schistose structure and pass into amphibolite-schist.

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[1] Sorby, *Q. J. Geol. Soc.* xxxvi. p. 82.

[2] Darwin, 'Geological Observations,' p. 162. Ramsay, "Geology of North Wales," in *Memoirs of Geol. Survey*, vol. iii. p. 182.

[3] *Op. cit.* p. 84.

[4] 'Volcanoes,' pp. 140, 300.

[5] 'Géologie Expérimentale,' p. 410.

The study of metamorphism and metamorphic rocks leads us from unaltered mechanical sediments at the one end, into thoroughly crystalline masses at the other. We are presented with a cycle of change wherein the same particles of mineral matter pass from crystalline rocks into sedimentary deposits, then by increasing stages of alteration back into crystalline masses, whence, after being reduced to detritus and redeposited in sedimentary formations, they may be once more launched on a similar series of transformations. The phenomena of metamorphism appear to be linked together with those of igneous action as connected manifestations of hypogene change.

PART II. EPIGENE OR SURFACE ACTION:

An Inquiry into the Geological Changes in progress upon the Earth's Surface.

On the surface of the globe and by the operation of agents working there, the chief amount of visible geological change is now effected. This branch of inquiry is not involved in the preliminary difficulty, regarding the very nature of the agents, which attends the investigation of plutonic action. On the contrary, the surface agents are carrying on their work under our eyes. We can watch it in all its stages, measure its progress, and mark in many ways how well it represents similar changes which for long ages previously must have been effected by similar means. But in the systematic treatment of this subject, a difficulty of another kind presents itself. While the operations to be discussed are numerous and often complex, they are so interwoven into one great network that any separation of them under different subdivisions is sure to be more or less artificial, and is apt to convey an erroneous impression. While, therefore, under the unavoidable necessity of making use of such a classification of subjects, we must bear always in mind that it is employed merely for convenience, and that in nature, superficial geological action must be viewed as a whole, since the work of each agent has close relations with that of the others and is not properly intelligible unless this connection be kept in view.

The movements of the air; the evaporation from land and sea; the fall of rain, hail, and snow; the flow of rivers and glaciers; the tides, currents, and waves of the ocean; the growth and decay of organised existence, alike on land and in the depths of the sea:—in short, the whole circle of movement, which is continually in progress upon the surface of our planet, are the subjects now to be examined. It would be desirable to adopt some general term to embrace the whole of this range of inquiry. For this end the word epigene may be suggested as a convenient term, and antithetical to hypogene, or subterranean action.

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[1] See G. H. Williams, *Amer. Journ. Sci.* 3rd ser. xxviii. (1884), p. 259.

The simplest arrangement of this part of Geological Dynamics will be into three sections:—

I. Air.—The influence of the atmosphere in destroying and forming rocks.

II. Water.—The geological functions of the circulation of water through the air and between sea and land, and the action of the sea.

III. Life.—The part taken by plants and animals in preserving, destroying, or originating geological formations.

The words destructive, reproductive, and conservative, employed in describing the operations of the epigene agents, do not necessarily imply that anything useful to man is destroyed, reproduced, or preserved. On the contrary, the destructive action of the atmosphere may cover bare rock with rich soil, while its reproductive effects may bury fertile soil under sterile desert. Again, the conservative influence of vegetation has sometimes for centuries retained as barren morass what might otherwise have become rich meadow or luxuriant woodland. The terms, therefore, are used in a strictly geological sense, to denote the removal and redeposition of material, and its agency in preserving what lies beneath it.

Section i. Air.

The geological action of the atmosphere arises partly from its chemical composition and partly from its movements. The composition of the atmospheric envelope has been already discussed (p. 32), and further information will be found under the head of Rain. The movements of the atmosphere are due to variations in the distribution of pressure or density, the law being that air always moves spirally from where the pressure is high to where it is low. Atmospheric pressure is understood to be determined by two causes, temperature and aqueous vapour. Since warm air, being less dense than cold air, ascends, while the latter flows in to take its place, the unequal heating of the earth's surface, by causing upward currents from the warmed portions, produces horizontal currents from the surrounding cooler regions inwards to the central ascending mass of heated air. The familiar land and sea breezes offer a good example of this action. Again, the density of the air lessens with increase of water-vapour. Hence moist air tends to rise as warmed air does, with a corresponding inflow of the drier and consequently heavier air from the surrounding tracts. Moist air, ascending and diminishing atmospheric pressure, as indicated by the fall of the barometer, rises into higher regions of the atmosphere, where it expands, cools, condenses into visible cloud and into showers that descend again to the earth.

Unequal and rapid heating of the air, or accumulation of aqueous vapour in the air, and possibly some other influences not yet properly understood, give rise to extreme disturbances of pressure, and consequently to storms and hurricanes. For instance, the barometer sometimes indicates in tropical storms a fall of an inch and a half in an hour, showing that somewhere about a twentieth part of the whole mass of atmosphere has, in that short space of time, been displaced over a certain area of the earth's surface. No such sudden change can occur without the most destructive tempest or tornado. In Britain the tenth of an inch of barometric fall in an hour is regarded as a large amount, such as only accompanies great storms.[1] The rate of movement of the air depends on the difference of barometric pressure between the regions from and to which the wind blows. Since much of the potency of the air as a geological agent depends on its rate of motion, it is of interest to note the ascertained velocity and pressure of wind as expressed in the subjoined table:[2]—

	Velocity in Miles per hour.	Pressure in Pounds per square foot.
Calm	0	0
Light breeze	14	1
Strong breeze	42	9
Strong gale	70	25
Hurricane	84	36

While the paramount importance of the atmosphere as the vehicle for the circulation of moisture over the globe, and consequently as powerfully influencing the distribution of climate and the growth of plants and animals, must be fully recognised by the geologist, he is specially called upon to consider the influence of the air in directly producing geological changes upon the surface of the land, and in augmenting the geological work done by water.

§ 1. Geological work of the atmosphere on land.

Viewed in a broad way, the air is engaged in the twofold task of promoting the disintegration of superficial rocks and in removing and redistributing the finer detritus. These two operations, however, are so intimately bound up with each other that they cannot be adequately understood unless considered in their mutual relations.

1. Destructive action.—Still dry air, not subject to much range of temperature, has probably little or no effect on minerals and rocks. The chemical action of the atmosphere takes place almost entirely through dissolved moisture. This subject is discussed in the section devoted to Rain. But sunlight produces remarkable changes on a few minerals. Some lose their colours (celestine, rose-quartz), others change it, as cerargyrite does from colourless to black, and realgar from red to orange-yellow. Some of these alterations may be explained by chemical modifications induced by such causes as the loss of organic matter and oxidation.

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[1] Buchan's 'Meteorology,' p. 266.

[2] For another statement see Czerny, *Peterman. Mitt.* 1876, Erganzungsheft.

Effects of lightning.—Hibbert has given an account of the disruption by lightning of a solid mass of rock 105 feet long, 10 feet broad, and in some places more than 4 feet high, in Fetlar, one of the Shetland Islands, about the middle of last century. The dislodged mass was in an instant torn from its bed and broken into three large and several lesser fragments. "One of these, 28 feet long, 17 feet broad, and 5 feet in thickness, was hurled across a high point of rock to a distance of 50 yards. Another broken mass, about 40 feet long, was thrown still farther, but in the same direction and quite into the sea. There were also many lesser fragments scattered up and down."[1]

The more usual effect of lightning, however, is to produce in loose sand or more compact rock patches of vitreous drops or bubbles coating the surface, also tubes termed *fulgurites*, which range up to 2½ inches in diameter. These tubes descend vertically, but sometimes obliquely, from the surface, occasionally branch, and rapidly lessen in dimensions till they disappear. They are formed by the actual fusion of the particles of the soil or rock surrounding the pathway of the electric spark. They have been most frequently found in loose sand. Abich has observed examples of such tubular perforations with vitreous walls in the porous reddish-white andesite at the summit of Little Ararat.[2] A piece of the rock about a foot long may be obtained perforated all over with irregular tubes having an average diameter of 3 centimetres. Each of these is lined with a blackish-green glass. As the whole summit of the mountain, owing to its frequent storms, is drilled in this manner, it is evident that the action of lightning may considerably modify the structure of the superficial portions of any mass of rock exposed on lofty eminences to frequent thunderstorms. Humboldt collected fulgurites from a trachyte peak in Mexico, and in two of his specimens the fused mass of the walls has actually overflowed from the tubes on the surrounding surface.[3]

Effects of changes of temperature.—Of far wider geological importance are the effects that arise among rocks and soils from the alternate expansion and contraction caused by daily or seasonal changes of temperature. In countries with a great annual range of temperature, considerable difficulty is sometimes experienced in selecting building-materials liable to be little affected by rapid or extreme variations in temperature, which induce an alternate expansion and contraction that prevents the joints of masonry from remaining close and tight.[1] If the daily thermometric variations are large, the effects are frequently striking. In Western America, where the climate is remarkably dry and clear, the thermometer often gives a range of more than 80° in the twenty-four hours. Thus in the Yellowstone district, at a height of 9000 feet above the sea, the author found the temperature of rocks exposed to the sun at noon to be more than 90° Fahr., and the thermometer at night to sink below 20°. In the Sahara and other African regions, as well as in Central Asia, the daily range is considerably greater. This rapid nocturnal contraction produces such a superficial strain as to disintegrate rocks into sand, or cause them to crack or peel off in skins or irregular pieces. Dr. Livingstone found in Africa (12° S. lat., 34° E. long.) that surfaces of rock which during the day were heated up to 137° Fahr., cooled so rapidly by radiation at night that, unable to sustain the strain of contraction, they split and threw off sharp angular fragments from a few ounces to 100 or 200 lb. in weight.[2] In the plateau region of North America, though the climate is too dry to afford much scope for the operation of frost, this daily vicissitude of temperature produces results that quite rival those usually associated with the work of frost. Cliffs are slowly disintegrated, the surface of arid plains is loosened, and the fine débris is blown away by the wind.

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[1] Hibbert's 'Shetland Islands,' p. 389, quoting from the MS. of Rev. George Low.

[2] *Sitzb. Akad. Wiss. Wien*, lx. (1870), p. 155.

[3] G. Rose, *Zeitsch. Deutsch. Geol. Ges.* xxv. p. 112; Gumbel, *op. cit.* xxxiv. (1882), p. 647; A. Wichmann, *op. cit.* xxxv. (1883), p. 849. Fusion by lightning was observed by De Saussure in hornblende-schist on the summit of Mont Blanc (see also F. Rutley, *Quart. Journ. Geol. Soc.* 1885, p. 152); by Ramond in mica-schist and limestone on a peak of the Pyrenees; by J. S. Diller on the basalt of Mount Thielson, Oregon, and on the top of Mount Shasta, California, *Amer. Journ. Sci.* Oct. 1884; by J. Eccles in glaucophane schist on Monte Viso, F. Rutley, *Quart. Journ. Geol. Soc.* xlv. (1889), p. 60.

Effects of wind.—The geological work directly due to the air itself is mainly performed by wind.[3] A dried surface of rock or soil, when exposed to wind, has the finer disintegrated particles blown away as dust or sand. This process, which takes place familiarly before our eyes on every street and roadway, over cultivated ground, as well as on surfaces with which man has not interfered, is most marked in dry climates. Aridity indeed is its main cause. Mr. Flinders Petrie, the able Egyptian archæologist and explorer, has brought forward evidence of the abrading influence of the wind upon mud-brick walls and other buildings, and he estimates that in some parts of the Nile delta about eight feet of soil has been swept away by the wind during the last 2600 years, or nearly four inches in a century.[4] Many old fortifications in Northern China have been laid bare to the very foundations by the removal of the surrounding soil through long-continued action of wind.[5] In the dry plateaux of

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[1] In the United States, with an annual thermometric range of more than 90° Fahr., this difficulty led to some experiments on the amount of expansion and contraction in different kinds of building-stones, caused by variations of temperature. It was found that in fine-grained granite the rate of expansion was ·000004825 for every degree Fahr. of increment of heat; in white crystalline marble it was ·000005668; and in red sandstone ·000009532, or about twice as much as in granite. Totten, in *Silliman's Amer. Journ.* xxii. p. 136. See *ante*, pp. 292, 299.

[2] Livingstone's 'Zambesi,' pp. 492, 516. According to Stanley, cold rain falling on these sun-heated African rocks causes them to split open and peel off. *Proc. Roy. Geog. Soc.* xx. (1876), p. 142.

[3] The general geological effects of wind are discussed by F. Czerny, *Petermann's Mittheil. Ergänzungsheft*, No. 48. *Nature*, xv. p. 231.

[4] *Proc. Roy. Geograph. Soc.* 1889, p. 648.

[5] Richthofen's 'China,' Berlin, 1877, i. p. 97.

North America, too, though no human memorials serve there as measures, extensive denudation from the same cause is in progress.

It is not merely that the wind blows away what has already been loosened and pulverised. The grains of dust and sand are themselves employed to rub down the surfaces over which they are driven. The nature and potency of the erosion done by sand-grains in rapid motion is well illustrated by the artificial sand-blast, in which a spray of fine siliceous sand, driven with great velocity, is made to etch or engrave glass.[1] The abrading and polishing effects of wind-blown sand have long been noticed on Egyptian monuments exposed to sand-drift from the Libyan desert.[2] Similar effects have been observed on dry volcanic plains of barren sand and ashes, as on the island of Volcano.[3] On the sandy plains of Wyoming, Utah, and the adjacent territories, surfaces even of such hard materials as chalcedony are etched into furrows and wrinkles, acquiring at the same time a peculiar and characteristic polish. There, also, large blocks of sandstone or limestone which have fallen from an adjacent cliff are attacked, chiefly at their base, by the stratum of drifting sand, until by degrees they seem to stand on narrow pedestals. As these supports are reduced in diameter the blocks eventually tumble over, and a new basal erosion leads to a renewal of the same stages of waste.[4] Hollows on rock-surfaces may also be noticed where grains of sand, or small pebbles kept in gyration by the wind, gradually erode the shallow cavities in which they lie.

As the result of the protracted action of wind upon an area exposed at once to great drought and to rapid vicissitudes of temperature, a continuous lowering of the general level takes place. The great sandy deserts thus produced represent, however, only a portion of the disintegration. Vast quantities of the finer dust are borne away by the wind into other regions, where, as will be immediately pointed out, they tend to raise the general level. Again, a considerable amount of fine dust and sand, blown into the neighbouring rivers, is carried down in their waters. In inland areas of drainage, indeed, like that of Central Asia, this transport does not finally remove the river-borne sediment from the basin of evaporation, but tends to fill up the lakes. Where, however, as in North America, rivers cross from the desert areas to the sea, there must be a permanent removal of wind-swept detritus by these streams. In the arid plateaux drained by the Colorado and its tributaries, so great has been the subaerial denudation that a thickness of thousands of feet of horizontal strata has been removed from the surface of level plains thousands of square miles in extent. This denudation, the extent of which is attested by the remaining cliffs and "buttes," or outliers, of the strata, appears to be in great measure due to the causes here discussed, augmented in some districts by the effects of occasional heavy storms of rain.

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[1] The student will find much valuable information on this subject in the experimental results obtained by Thoulet, *Comptes Rend.* civ. p. 381. *Ann. des Mines*, 1887 ; and in the essay by Walther cited below.

[2] An excellent account of the denudation phenomena of the Egyptian deserts will be found in an essay by J. Walther in vol. xvi. (1891) of the *Abhand. Königl. Sächsisch. Gesellsch. d. Wissensch.* The polishing of rocks by the sand of the Sahara is described by M. Choisy in his report 'Documents relatifs à la mission dirigée au Sud de l'Algérie,' 1890, p. 327.

[3] Kayser, *Z. Deutsch. Geol. Ges.* xxvii. p. 966.

[4] See Gilbert in Wheeler's *Report of U. S. Geograph. Surv. W. of 100th Meridian*, iii. p. 82. W. P. Blake, *Union Pacific Railroad Report*, v. pp. 92, 230. *Amer. Journ. Sci.* xx. (1885), p. 178. Naumann, *Neues Jahrb.* 1874, p. 337. Cazalis de Fondouce, *Assoc. Française*, 1879, p. 646. Many good illustrations are given by Walther in the essay above cited.

One further effect produced by air in violent motion may be seen in the destruction caused by cyclones. Not only are houses demolished, with much damage to other property and loss of life, but permanent changes of more or less importance are produced upon the surface of a country. Loose rocks on the face of cliffs are hurled down, and blocks of stone and loose gravel are swept away. But the most obvious effects are those in wooded districts, where the trees are prostrated far and near in the path of the storm. On the 18th and 19th of May 1883, a succession of hurricanes passed over the States of Illinois and Wisconsin, with such fury that the brick chimney of a factory was carried to a distance of three-quarters of a mile, an entire house was lifted into the air and blown to pieces, and an oak two feet in diameter was dashed through a house. When such a storm passes over forest-ground in temperate latitudes, the surface-drainage may be so obstructed by the fallen stems, that marsh-plants spring up, and eventually the site of a forest may be occupied by a peat-moss (p. 478).

2. **Reproductive action.**—Growth of Dust. The fine dust and sand resulting from the general superficial disintegration of rocks would, if left undisturbed, accumulate *in situ* as a layer that would serve to protect the still undecayed portions underneath. Such a layer, indeed, partially remains, but, being liable to continual attack and removal, may be taken to represent, where it occurs, the excess of disintegration over removal. In the vast majority of cases, however, the superficial coating of loose material is not due merely to the direct action of the sun's rays and of the air, but in far greater degree to the work of rain, aided by the co-operation of plants and animals. To the layer thus variously produced, the name of Soil is given. Its formation is described at p. 351.

That wind plays an effective part in the re-distribution of superficial detritus is demonstrated by every cloud of dust blown from dessicated ground. We only need to take into account the multiplying power of time, to realise how extensively the soil of a district may be lowered, or, in other cases, may be replenished and heightened by the dust-storms of centuries. Dust and sand, intercepted by the leaves of plants, gradually descend into the soil, whither they are washed down by rain, so that even a permanently grassy surface may be slowly and imperceptibly heightened in this way, and a soil may be formed differing considerably in chemical composition from what would result merely from the decay of the subsoil.[1]

On the sites of ancient monuments and cities, this reproductive action of the atmosphere can be most impressively seen and most easily measured. In Europe, on sites still inhabited by an abundant population, the deep accumulations beneath which ancient ruins often lie are doubtless mainly to be assigned to the successive destructions and rebuildings of generation after generation of occupants. But at Nineveh, Babylon, and many other eastern sites, mounds which have been practically untouched by man for many centuries consist of fine dust and sand gradually drifted by the wind round and over abandoned cities, and protected and augmented by the growth of vegetation.[1] In those arid lands, the air is often laden with fine detritus, which drifts like snow round conspicuous objects and tends to bury them up in a dust-drift. In Central Asia, even when there is no wind, the air is often thick with fine dust, and a yellow sediment settles from it over everything. In Khotan an exceedingly fine dust sometimes so obscures the sun that even at midday one cannot read large print without a lamp. This dust, deposited on the soil, heightens and fertilises it, and is regarded by the inhabitants as a kind of manure, without which the ground would be barren.[2]

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[1] C. Reid, *Geol. Mag.* 1884, p. 165.

Loess.—This name has been given to a remarkable deposit, first described in the valley of the Rhine, but which has been found to cover vast areas both in the Old World and in the New.[3] It is usually a yellowish homogeneous clay or loam, unstratified, and presenting a singular uniformity of composition and structure. When carefully examined, its quartz-grains are found to be remarkably angular, and its mica-flakes, instead of being deposited horizontally, as they are by water, occur dispersedly in every possible position and with no definite order.[4] The chief constituent of loess is always hydrated silicate of alumina, in which the scattered grains of quartz and flakes of mica are distributed. It is in some measure calcareous, the lime being here and there segregated into curious concretionary forms (Lössmänchen, Lösspuppen, p. 512) by the action of infiltrating water. Though a firm unstratified mass, it is traversed by innumerable tubes, formed by the descent of roots and mostly crusted with carbonate of lime. These have generally a vertical position, and ramify downwards. Where the surface is covered with vegetation, they may be seen occupied by rootlets to a depth of a foot or a few feet from the surface. By means of these pipes a tendency is given to a vertical jointing of the mass. With these characters, the loess unites a remarkable peculiarity in respect of its organic remains, which consist chiefly of land-shells, sometimes in immense numbers, likewise of the bones of various herbivorous and carnivorous mammals, which are either identical with or closely allied to living species that abound on steppes and grassy plains. Freshwater shells are usually rare, and marine forms do not occur. Loess is found at all elevations, up to 5000 feet among the Carpathians, 8000 feet in Shansi, China, and probably to still higher altitudes further west. In hilly regions it fills up the valleys, shading off on either side up the slopes into the angular débris of the adjoining rock. Elsewhere, it spreads over the surface so as completely to conceal the original inequalities of the ground. In Northern China, Richthofen found it to have a thickness of 1500 or possibly over 2000 feet, and to be cut into deep valleys and precipitous ravines, with cliffs 500 feet high, which are excavated into tiers of chambers and passages by a teeming population.[1] In the arid tracts of North America the loess or "adobe" is estimated to be sometimes 2000 or 3000 feet thick.[2]

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[1] The rubbish which, in the course of many centuries, has accumulated above the foundations of the Assyrian buildings at Kouyunjik was found by Layard to be in some places twenty feet deep. It consisted partly of ruins, but mostly of fine sand and dust blown from off the plains and mixed with decayed vegetable matter. Layard, 'Nineveh and its Remains,' 3rd edit. ii. p. 120. See also Richthofen's 'China,' i. p. 97.

[2] Johnson's 'Journey to Holi, the capital of Khotan,' *Journ. Geog. Soc.* xxxvii. 1867, p. 1. H. B. Guppy, *Nature*, xxiv. (1881), p. 126.

[3] The calcareous clays of the arid regions of North America have been largely used for the manufacture of sun-dried bricks called in Spanish "adobe,"—a term which has been proposed as a geological designation for these deposits. I. C. Russell, *Geol. Mag.* 1889, p. 291.

[4] See Mr. Russell's paper cited in the previous note, p. 294.

Various theories have been proposed in explanation of this singular deposit. By some it has been referred to the operation of the sea; by others to the work of lakes or of rivers. But its wide extent, its independence of the altitude or contours of the ground, its uniform and unstratified character, the unworn condition of its component particles, and the nature of its organic remains, show that it cannot be assigned to the action of large bodies of water. Richthofen propounded in 1870 the opinion that the loess is mainly due to the long-continued drifting and deposit of fine dust by wind over areas more or less covered with grassy vegetation, aided by the washing influence of rain, and this view has been widely accepted. Where rain is distributed somewhat equally throughout the year little dust is formed; but where dry and wet seasons alternate, as in Central Asia, vast quantities of dust may be moved during the months of dry weather. When the dust falls on bare ground, it is eventually swept away by the wind; but where it settles down on ground covered with vegetation it is in great measure protected from further transport, and thus heightens the soil.[3]

For atmospheric accumulations of this nature, Trautschold has proposed the name *eluvium.* They originate *in situ*, or at least only by wind-drift, whereas *alluvium* requires the operation of water, and consists of materials brought from a greater or less distance.[4] For wind-formed deposits the term "æolian" is sometimes used.

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[1] See Richthofen's description, *Geol. Mag.* 1882, p. 293, and his 'China,' above cited.

[2] Russell, *Geol. Mag.* 1889, p. 292.

[3] Richthofen, *Geol. Mag.* 1882, p. 297. For some of the more important contributions to this subject, see Richthofen's 'China,' vols. i. and ii.; also *Verh. Geol. Reichs.* 1876, p. 289; E. Tietze, *Verh. Geol. Reichs.* 1878, p. 113; 1881, p. 37; *Jahrb. Geol. Reichs.* 1881, p. 80; 1882, p. 11; 1883, p. 279; R. Pumpelly, *Amer. Journ. Sci.* xvii. (1879): E. W. Hilgard, *op. cit.* xviii. (1879), p. 106 (p. 427); I. C. Russell, *Geol. Mag.* 1889, pp. 288, 342; F. Wahnschaffe, *Z. Deutsch. Geol. Ges.* 1886. *Jahrb. Preuss. Landesanst.* 1889, p. 328. A. Sauer, *Zeitsch. für Naturwissensch.* lxii. (1889); and *postea*, Book VI. Part V. Sect. i. On the loess of Alsace, see E. Schumacher, *Commiss. Landesuntersuch. Elsass-Lothringen*, vol. ii. Part I. (1889), p. 79; on the loess of the Pampas, S. Roth, *Zeitsch. Deutsch. Geol. Gesell.* xl. (1888), p. 422.

[4] *Z. Deutsch. Geol. Ges.* xxxi. p. 578.

Sandhills or Dunes.—Winds blowing continuously upon sand drive it onward, and pile it into irregular heaps and ridges, called "dunes." This takes place more especially on windward coasts either of the sea or of large inland lakes, where sandy shores are exposed to the drying influence of solar heat and wind; but similar effects may be seen even in the heart of a continent, as in the sandy deserts of the Sahara,[1] Arabia, and in the arid lands of Utah, Arizona, &c. The dunes travel in parallel, irregular, and often confluent ridges, their general direction being transverse to the prevalent course of the wind. Local wind-eddies cause many irregularities of form. In humid climates, rain-water or the drainage of small brooks is sometimes arrested between the ridges to form pools (*étangs* of the French coasts), where formations of peat occasionally take place. On the coast of Gascony, the sea for 100 miles is so barred by sand-dunes that in all that distance only two outlets exist for the discharge of the drainage of the interior. As fast as one ridge is driven away from a beach another forms in its place, so that a series of huge sandy billows, as it were, is continually on the move from the sea-margin towards the interior. A stream or river may temporarily arrest their progress, but eventually they push the obstacle aside or in front of them. In this way the river Adour, on the west coast of France, has had its mouth shifted two or three miles. Occasionally, as at the mouths of estuaries, the sand is blown across, so as gradually to exclude the sea, and thus to aid the fluviatile deposits in adding to the breadth of the land. In Fig. 90 a stream (*e e*) is represented as crossing a plain (*a*) at the margin of the sea or of a large inland sheet of water, bounded by a range of sand-dunes (*b b*) extending between the two lines of cliff (*c g*). The stream has been turned to its right bank by the advance of the dunes driven by a prevalent wind blowing in the direction of the arrows. A brook (*f*) has been arrested among the sandy wastes, whence, after forming a few pools, it finds egress by soaking through the sandy barrier.

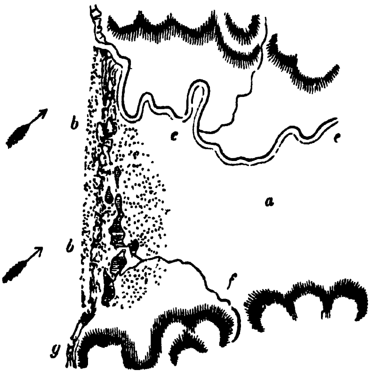

Fig. 90.—Sand-dunes affecting land-drainage (*B.*)

The nature of the grains of sand depends on the character of the rocks from the destruction by which they are derived, and their form and size are largely regulated by the force of the wind and the relative share taken by subaerial and subaqueous action in their production. Quartz is the most frequent constituent, but the other minerals of rocks also occur, especially those which are most capable of resisting mechanical trituration. In some cases, organic remains, such as particles of shells, nullipores, &c., form the main mass of the sand (see p. 336).[1] The sand-grains liberated by inland subaerial disintegration are apt to be more angular than those brought within the influence of the wind along a shore-line.[2]

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[1] For an account of the sand-dunes of the Sahara see 'Documents relatifs à la Mission dirigée au Sud de l'Algérie,' A. Choisy, 1890, p. 323.

Perfect "ripple-marks" (p. 507) may often be observed on blown sand. The sand-grains, pushed along by the wind, travel up the long slopes and fall over the steep slopes. Not only do the particles travel, but the ridges also more slowly follow each other, as in Fig. 91.[3]

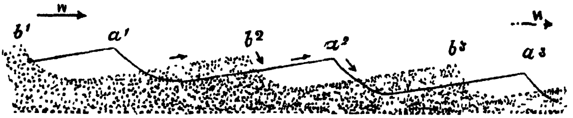

Fig. 91.—Diagram of Ripples in blown Sand. The ridges b^1, b^2, b^3, impelled in the direction of W W, successively come to occupy the hollows a^1, a^2, a^3 (*B.*)

The western sea-board of Europe, exposed to prevalent westerly and south-westerly winds, affords many instructive examples of these æolian or wind-formed deposits. The coast of Norfolk is occasionally fringed with sand-hills 50 to 60 feet high. On parts of the coast of Cornwall,[4] the sand consists mainly of fragments of shells and corallines, and through the action of rain upon these calcareous particles, becomes sometimes cemented by carbonate of lime (or oxide of iron) into a stone so compact as to be fit for building purposes. Long tracts of blown sand are likewise found on the Scottish and Irish[5] coast-lines. Sand-dunes extend for many leagues along the French coast, and thence, by Flanders and Holland, round to the shores of Courland and Pomerania. On the coast of Holland they are sometimes, though rarely, 260 feet high—a common average height being 50 to 60 feet.[6]

The breadth of this maritime belt of sand varies considerably. On the east coast of Scotland it ranges from a few yards to 3 miles; on the opposite side of the North Sea it attains on the Dutch coast sometimes to as much as 5 miles. The rate of progress of the dunes towards the interior depends upon the wind, the direction of the coast, and the nature of the ground over which they have to move. On the low and exposed shores of the Bay of Biscay, when not fixed by vegetation, they travel inland at a rate of about 16½ feet per annum, in Denmark at from 3 to 24 feet. In the course of their march they envelop houses and fields; even whole parishes and districts once populous have been overwhelmed by them.[7]

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[1] Mr. Russell (*Geol. Mag.* 1889) refers to some parts of the sands of the arid lands of North America as being composed mainly of the cases of cyprids, blown away from the beds of dried-up lakes.

[2] Engravings of some of the sand-grains from the Egyptian deserts are given by Walther in the essay already cited.

[3] On the origin of ripple-mark, see Book IV. Part I. p. 509.

[4] Ussher, *Geol. Mag.* (2), vi. p. 307, and authorities there cited. The upper parts of the blown sand are sometimes crowded with land-shells, the decay of which furnishes the cementing material (see Fig. 76).

[5] See Kinahan, *Geol. Mag.* viii. p. 155.

[6] On the growth of Holland through the operation of the wind and the sea, see Élie de Beaumont, 'Leçons de Géologie pratique,' i. A detailed description of the dunes of Holland is given by J. Lorié, *Arch. Musée Teyler*, sér. ii. vol. iii. Part V. (1890), p. 375. For an account of the sand-dunes of Western Europe, see W. Topley, *Pop. Science Rev.* xiv. (1875), p. 133.

[7] This destruction has more recently been averted to a great extent by the planting of pine forests, the turpentine of which has become the source of a large revenue.

Along the margins of large lakes and inland seas many of the phenomena of an exposed sea-coast are repeated on a scarcely inferior scale. Among these must be included sand-dunes, such as those which, reaching heights of 100 to 200 feet on the south-eastern shores of Lake Michigan, have entombed forests, the tops of the trees being still visible above the drifting sand. Large dunes occur also on the eastern borders of the Caspian Sea, where the sand spreads over the desert region between that sea and the Sea of Aral, into which latter sheet of water the spread of the sand has driven the course of the Oxus, once a tributary of the Caspian.

In the interior of continents, the existence of vast arid wastes of loose sand, situated far inland and remote from any sheet of fresh water, suggest curious problems in physical geography. In some instances, these tracts have been at a comparatively recent geological period covered by the sea. Yet the disintegration of rock in torrid and rainless regions is so great (*ante*, p. 328), that the existing sand is doubtless mainly, if not entirely, of subaerial origin. The sandy deserts of the high plateaux of Western North America, which have never been under the sea for a long series of geological ages, show, as we have already found (p. 329), the mode and progress of their formation from atmospheric disintegration alone. In Asia lie the vast deserts of Gobi, where in some places ancient cities have been buried under the sand.[1] In Rajputana, wide tracts of sandy desert present a succession of nearly parallel ridges or waves of sand, varying up to 180 feet from trough to crest, and presenting long gentle slopes towards south-west, whence the prevalent winds blow, but with north-eastern fronts as steep as the sand will lie.[2] To the east of the Red Sea stretch the great sand-wastes of Arabia; and to the west those of Libya. The sandy wastes of the Sahara have in recent years been partially explored, especially by French observers from the Algerian frontier. According to M. Rolland, the sand is entirely due to the action of the wind, and though there is a transport of sand and fine dust, the position of the large dunes, sometimes 70 metres in height, remains on the whole unchanged.[3] In the south-east of Europe, over the steppes of southern Russia and the adjacent territories, wide areas of sandy desert occur. Captain Sturt found vast deserts of sand in the interior of Australia, with long bands of dunes 200 feet high, united at the base and stretching in straight lines as far as the eye could reach.[4]

Some of the most remarkable æolian formations are in course of accumulation at Bermuda and other coral-islands. The finer coral-sand, with remains of shells, echinoderms, calcareous algæ, and other organisms, is driven by the wind into dunes, the surface of which by the action of rain-water soon becomes cemented into coherence, while by degrees the whole mass of calcareous débris is converted into a hard compact rock which rings under the hammer. The highest point of Bermuda is 245 feet above the sea, and the whole land up to that height is composed of these hardened calcareous æolian deposits.[1]

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[1] For important information regarding the Central Asiatic wastes, see Richthofen's 'China,' i. Also Tchihatchef, *Brit. Assoc.* 1882, p. 356. T. D. Forsyth, *Journ. Roy. Geog. Soc.* xlvii. (1878), p. 1.

[2] Major C. Strahan in 'Report of Survey of India,' 1882-83.

[3] G. Rolland, *Bull. Soc. Géol. France*, 3rd sér. x. p. 30. See also A. Parran, *op. cit.* xviii. (1890), p. 245.

[4] For accounts of sand-dunes, their extent, progress, structure, and the means employed to arrest their progress, the student may consult Andersen's 'Klitformationen,' 1 vol. 8vo, Copenhagen, 1861; Laval in *Annales des Ponts-et-Chaussées*, 1847, 2me sem. Marsh's 'Man and Nature,' 1864, and the works cited by him. Forchhammer, *Edin. New Phil. Journ.* xxxi. (1841), p. 61. Élie de Beaumont, 'Leçons de Géologie pratique,' vol. i. p. 183. Winkler, *Cong. Internat. Géol.* 1878, p. 181. Information regarding the sands of the interior of continents will be found in Palgrave's 'Travels in Arabia'; Blake, in *Union Pacific Railroad Report*, v.; Tristram, 'The Great Sahara,' 1860; Desor, "Le Sahara, ses différents types de déserts," *Bull. Soc. Sci. Nat. Neufchâtel*, 1864; E. Fuchs, *Petermann's Mittheil.* 1879; A. Pomel, *Assoc. Française*, 1877, p. 428; G. Rolland, *Bull. Soc. Géol. France*, 3me sér. x., *La Nature*, 1882, *Soc. de Géog.* 1890; Richthofen's 'China,' i.; I. C. Russell on the subaerial deposits of North America, *Geol. Mag.* 1889, p. 289.

Dust-showers, Blood-rain.—Besides the universal transport and deposit of dust and sand already described, a phenomenon of a more aggravated nature is observed in tropical countries, where great droughts are succeeded by violent hurricanes. The dust or sand of deserts and of dried lakes or river-beds is then sometimes borne away into the upper regions of the atmosphere, where, meeting with strong aerial currents which may transport it for many hundreds of miles, it descends again to the surface, in the form of "red fog," "sea-dust," or "sirocco-dust." This transported material, usually of a brick-dust or cinnamon colour, is occasionally so abundant as to darken the air and obscure the sun, and to cover the decks, sails, and rigging of vessels which may even be hundreds of miles from land. Rain falling through such a dust-cloud mixes with it, and descends, either on sea or land, as what is popularly called "blood-rain." Occasionally the dust is brought down to the surface of the ground by snow.

This phenomenon is frequent on the north-west of Africa, about the Cape Verd Islands, in the Mediterranean, and over the bordering countries. A microscopic examination of this dust by Ehrenberg led him to the belief that it contains numerous diatoms of South American species; and he inferred that a dust-cloud must be swimming in the atmosphere, carried forward by continuous currents of air in the region of the trade-winds and anti-trades, but suffering partial and periodical deviations. But much of the dust seems to come from the sandy plains and desiccated pools of the north of Africa. Daubrée recognised in 1865 some of the Sahara sand which fell in the Canary Islands. On the coast of Italy, a film of sandy clay, identical with that from parts of the Libyan desert, is occasionally found on windows after rain. In the middle of last century an area of Northern Italy, estimated at about 200 square leagues, was covered with a layer of dust which in some places reached a depth of one inch. In 1846 the Sahara dust reached Lyons, and it is said to have been since detected as far as Boulogne-sur-Mer. Should the travelling dust encounter a cooler temperature, it may be brought to the ground by snow, as has happened in the North of Italy, and more notably in the east and south-east of Russia, where the snows are sometimes rendered dirty by the dust raised by winds on the Caspian steppes.[2] It is easy to see how widespread deposits of dust may arise, mingled with the soil of the land, and with the silt and sand of lakes, rivers, or the sea; and how the minuter organisms of tropical regions may thus come to be preserved in the same formations with the terrestrial or marine organisms of temperate latitudes.[3]

The transport of volcanic dust by wind, already referred to (p. 216), may be again cited here, as another example of the geological work of the atmosphere. Thus, from the Icelandic eruptions of 1874-75, vast showers of fine ashes not only fell on Iceland to a depth of six inches, destroying the pastures, but were borne over the sea and across Scandinavia to the east coast of Sweden.[1] The remarkable sunsets of Europe during the winter and spring of 1883-84 are ascribed to the diffusion of the fine dust from the great Krakatoa eruption of August 1883 (p. 214). Considerable deposits of volcanic material may thus be formed in the course of time even far remote from any active volcano.

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[1] Nelson, *Q. J. Geol. Soc.* ix. p. 200. Wyville Thomson's 'Atlantic,' vol. i., and *ante*, p. 128.

[2] Consult an interesting paper by C. von Camerlander on snow with dust which fell in Silesia, Moravia, and Hungary in February 1888, *Jahrb. Geol. Reichsanst.* xxxviii. (1888), p. 281.

[3] See Humboldt on dust whirlwinds of Orinoco, 'Aspects of Nature'; also Maury, 'Phys. Geog. of Sea,' chap. vi.; Ehrenberg's 'Passat-Staub und Blut-Regen,' *Berlin Akad.* 1847. A von Lasaulx on so-called "cosmic dust," Tschermak's *Mineral. Mittheil.* 1880, p. 517.

Transportation of Plants and Animals.—Besides the transport of dust for distances of perhaps thousands of miles, wind may also transport living seeds or spores, which, finally reaching a congenial climate and soil, may survive and spread. We are yet, however, very ignorant as to the extent to which this cause has actually operated in the establishment of any given local flora. With regard to the minute forms of vegetable life, indeed, there can be no doubt as to the efficacy of the wind to transport them across vast distances on the surface of the globe. Upwards of 300 species of diatoms have been found in the deposits left by dust-showers. Among the millions of organisms thus transported it is hardly conceivable that some should not fall still alive into a fitting locality for their continued existence and the perpetuation of their species. Animal forms of life are likewise diffused through the agency of winds. Insects and birds are often met with at sea, many miles distant from the land from which they have been blown. Such organisms are in this way introduced into oceanic islands, as is well shown in the case of Bermuda. Hurricanes, by which large quantities of water are sucked up from lakes and rivers over which they pass, may also transport part of the fauna of these waters to other localities.

Efflorescence products.—Among the formations due in large measure to atmospheric action must be included the saline efflorescences which form upon the ground in the dry interior basins of continents. The steppes of Southern Russia, and the plains round the Great Salt Lake of Utah, may be taken as illustrative examples. Water, rising by capillary attraction through the soil to the surface, is there evaporated, leaving behind a white crust, by which the upper portion of the soil is covered and permeated. The incrustations consist of sodium-chloride, sodium- and calcium-carbonates, calcium- sodium- and potassium-sulphates in various proportions, these being the salts present also in the salt lakes of the same regions (p. 408).[2]

§ 2. Influence of the Air on Water.

The results of the action of the air upon water will be more fitly noticed in the section devoted to Water. It will be enough to notice here—

1. **Ocean currents.**—These are mainly dependent for their existence

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[1] Nordenskiold, *Geol. Mag.* (2), iii. p. 292. F. Zirkel, *Neues Jahrb.* 1879, p. 399 G. vom Rath, *ibid.* p. 506, and *ante*, p. 216.

[2] On efflorescence of Great Salt Lake region, see *Exploration of 40th Parallel*, i. sect. v. Consult also E. Tietze, "Entstehung der Salzsteppen," *Jahrb. Geol. Reichsanst.* 1877, and H. le Chatelier on the salt-crusts of Algeria, *Comptes Rend.* lxxxiv. p. 396.

and direction on the circulation of the atmosphere. The in-streaming of air from cooler latitudes towards the equator causes a drift of the sea-water in the same direction. As, owing to the rotation of the earth these aerial currents tend to take a more and more westerly trend in approaching the equator, they communicate this trend to the marine currents, which, likewise moving into regions with a greater velocity of rotation than their own, are all the more impelled in the same westerly direction. Hence the dominant equatorial current which flows westward across the great ocean. Owing, however, to the position of the continents across its path, this great current cannot move uninterruptedly round the earth. It is split into branches which turn to right and left, and, bathing the shores of the land, carry some of the warmth of the tropics into more temperate latitudes. Return currents are thus generated from cooler latitudes towards the equator (p. 434).

2. Waves.—The impulse of the wind upon a surface of water throws that surface into pulsations which range in size from mere ripples to huge billows. Long-continued gales from the seaward upon an exposed coast indirectly effect much destruction, by the formidable battery of billows which they bring to bear upon the land (p. 444). Wave-action is likewise seen in a marked manner when wind blows strongly across a broad inland sheet of water, such as Lake Superior (p. 406).

3. Alteration of the Water-level.—Wind blowing freshly across a lake or narrow sea drives the water before it, and keeps it temporarily at a higher level on the farther or windward side. In a tidal sea, such as that which surrounds Great Britain, and which sends abundant long arms into the land, a high tide and a gale are sometimes synchronous. This conjunction makes the high tide rise to a greater height than elsewhere in those bays or firths which look windward, occasionally causing considerable damage to property by the flooding of warehouses and stores, with even a sensible destruction of cliffs and sweeping away of loose materials. On the other hand, a wind from the opposite quarter coincident with an ebb tide, by driving the water out of the inlet, makes the water-level lower than it would otherwise be. In inland seas where tides are small or imperceptible, considerable oscillations of water-level may arise from the action of the wind. At Naples, for example, a long-continued south-west wind raises the level of the water several inches. Similar results attend prolonged gales on large fresh-water lakes (p. 405).

Rapid and great diminution of atmospheric pressure may also cause a rise in the level of the sea and produce great destruction (p. 437).

Section ii. Water.

Of all the terrestrial agents by which the surface of the earth is geologically modified, by far the most important is water. We have already seen, when following hypogene changes, how large a share is taken by water in the phenomena of volcanoes and in other subterranean processes. Returning to the surface of the earth and watching the operations of the atmosphere, we soon learn how important a part of these is sustained by the aqueous vapour by which the atmosphere is pervaded.

The substance which we term water exists on the earth in three well-known forms—(1) gaseous, as invisible vapour; (2) liquid, as water; and (3) solid, as ice. The gaseous form has already been noticed as one of the characteristic ingredients of the atmosphere (p. 32). Vast quantities of vapour are continually rising from the surface of the seas, rivers, lakes, snow-fields, and glaciers of the world. This vapour remains invisible until the air containing it is cooled down below its dew-point, or point of saturation,—a result which follows upon the union or collision of two aerial currents of different temperatures, or the rise of the air into the upper cold regions of the atmosphere, where it is chilled by expansion, by radiation, or by contact with cold mountains. According to recent researches, condensation appears only to take place on free surfaces, and the formation of cloud and mist is explained by condensation upon the fine microscopic dust of which the atmosphere is full.[1] At first minute particles of water-vapour appear, which either remain in the liquid condition, or, if the temperature is sufficiently low, are frozen into ice. As these changes take place over considerable spaces of the sky, they give rise to the phenomena of clouds. Further condensation augments the size of the cloud-particles, and at last they fall to the surface of the earth, if still liquid, as rain; if solid, as snow or hail; and if partly solid and partly liquid, as sleet. As the vapour is largely raised from the ocean-surface, so in great measure it falls back again directly into the ocean. A considerable proportion, however, descends upon the land, and it is this part of the condensed vapour which we have now to follow. Upon the higher elevations it falls as snow, and gathers there into snow-fields, which, by means of glaciers, send their drainage towards the valleys and plains. Elsewhere it falls chiefly as rain, some of which sinks underground to gush forth again in springs, while the rest pours down the slopes of the land, feeding brooks and torrents, which, swollen further by springs, gather into broader and yet broader rivers that bear the accumulated drainage of the land out to sea. Thence once more the vapour rises, condensing into clouds and rain to feed the innumerable water-channels by which the land is furrowed from mountain-top to seashore.[2]

In this vast system of circulation, ceaselessly renewed, there is not a drop of water that is not busy with its allotted task of changing the face of the earth. When the vapour ascends into the air, it is comparatively speaking chemically pure. But when, after being condensed into visible form, and working its way over or under the surface of the land, it once more enters the sea, it is no longer pure, but more or less loaded with material taken by it out of the air, rocks, or soils through which it has travelled. Day by day the process is advancing. So far as we can tell, it has never ceased since the first shower of rain fell upon the earth.

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[1] Coulier and Mascart, *Naturforscher*, 1875, p. 400. Aitken, *Proc. Roy. Soc. Edin.* Dec. 1880.

[2] For estimates of the distribution of rain over the globe, see Murray, *Scottish Geol. Mag.* 1887.

We may well believe, therefore, that it must have worked marvels upon the surface of our planet in past time, and that it may effect vast transformations in the future. As a foundation for such a belief let us now inquire what it can be proved to be doing at the present time.

§ 1. Rain.

Rain effects two kinds of changes upon the surface of the land. (1) It acts *chemically* upon soils and stones, and, sinking under ground, continues, as we shall find, a great series of similar reactions there. (2) It acts *mechanically*, by washing away loose materials, and thus powerfully affecting the contours of the land.

1. **Chemical Action.**—This depends mainly upon the nature and proportion of the substances abstracted by rain from the air in its descent to the earth. Rain absorbs a little air, which always contains carbonic acid as well as other ingredients, in addition to its nitrogen and oxygen (p. 32). Rain thus washes the air and takes impurities out of it, by means of which it is enabled to work many chemical changes that it could not accomplish were it to reach the ground as pure water.

Composition of Rain-water.—Numerous analyses of rain-water show that it contains in solution about 25 cubic centimetres of gases per litre.[1] An average proportional percentage is by measure—nitrogen, 64·47 : oxygen, 33·76 ; carbonic acid, 1·77. Carbonic acid being more soluble than the other gases, is contained in rain-water in proportions between 30 and 40 times greater than in the atmosphere. Oxygen too is more soluble than nitrogen. These differences acquire a considerable importance in the chemical operations of rain. Other substances are present in smaller quantities. In England there is an average of 3·95 parts of solid impurity in 100,000 parts of rain.[2] Nitric acid sometimes occurs in marked proportions : at Bâle it was found to reach a maximum of 13·6 parts in a million, with 20·1 parts of nitrate of ammonia. Sulphuric acid likewise occurs, especially in the rain of towns and manufacturing districts.[3] Sulphates of the alkalies and alkaline earths have been detected in rain. But the most abundant salt is chloride of sodium, which appears in marked proportions on coasts, as well as in the rain of towns and industrial districts. Rain taken at the Land's End in Cornwall during a strong south-west wind was found to contain 2·180 of chlorine, or 3·591 parts of common salt, in every 10,000 of rain.

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[1] Baumert, *Ann. Chem. Pharm.* lxxxviii p. 17. The proportion of carbonic acid found by Peligot was 2·4. See also Bunsen, *op. cit.* xciii. p. 20. Roth, 'Chem. Geol.' i. p. 44. Angus Smith, 'Air and Rain,' 1872, p. 225.

[2] *Rivers Pollution Commission*, 6th Rep. p. 29.

[3] The occurrence of sulphuric and nitric acids in the air, especially noticeable in large towns, leads to considerable corrosion of metallic surfaces, as well as of stones and lime. The mortar of walls may often be observed to be slowly swelling out and dropping off, owing to the conversion of the lime into sulphate. Great injury is likewise done, from a similar cause, to marble monuments in exposed graveyards. See Angus Smith, 'Air and Rain,' p. 444. Geikie, *Proc. Roy. Soc. Edin.* 1879-80, p. 518.

The mean proportion of chlorine over England is about 0·022 in every 10,000 parts of rain; at Ootacamund 0·003 to 0·004.[1]

In washing the air, rain carries down also inorganic particles or motes floating there; likewise organic dust and living germs.[2] As the result of this process the soil comes to be not merely watered but fertilised by the rain. Angus Smith cites the experience of J. J. Pierre, who found by analysis that in the neighbourhood of Caen, in France, a hectare of land receives annually from the atmosphere by means of rain[3]:—

Chloride of sodium	37·5	kilogrammes.
,, potassium	8·2	,,
,, magnesium	2·5	,,
,, calcium	1·8	,,
Sulphate of soda	8·4	kilogrammes.
,, potash	8·0	,,
,, lime	6·2	,,
,, magnesia	5·9	,,

Not only rain, but also dew and hoar-frost abstract impurities from the atmosphere. The analyses performed by the Rivers Pollution Commission show that dew and hoar-frost, condensing from the lower and more impure layers of the air, are even more contaminated than rain, as they contain on an average in England 4·87 parts of solid impurity in 100,000 parts, with 0·198 of ammonia.[4]

It is manifest that rain reaches the surface by no means chemically pure water, but having absorbed from the air various ingredients which enable it to accomplish a series of chemical changes in rocks and soils. So far as we know at present, the three ingredients which are chiefly effective in these operations are oxygen, carbonic acid, and organic matter. As soon as it touches the earth, however, rain-water begins to absorb additional impurities, notably increasing its proportion of carbonic acid and of organic matter, from decomposing animals and plants. Among the organic products most efficacious in promoting the corrosion of minerals and rocks are the so-called ulmic or humous substances that form with alkalies and alkaline earths soluble compounds, which are eventually converted into carbonates.[1] Hence as rain-water, already armed with gases absorbed from the atmosphere, proceeds to take up these organic acids from the soil, it is endowed with considerable chemical activity even at the very beginning of its geological career.

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[1] Angus Smith, 'Air and Rain.' *Rivers Pollution Commission*, 6th Rep. 1874, p. 425. During a westerly gale on the Atlantic coasts of Britain, when the sea is white with foam, the air, elsewhere clear, may be seen to be quite misty alongshore from the clouds of fine spray swept by the wind from the crests of the breakers. This salt-water dust is borne far inland. From the investigations carried on at the Agricultural Laboratory, Rothamsted, it appears that the average proportion of chlorine is 2·01 per million parts of rain, which in a rainfall of 31·65 inches is equal to a discharge of 24 lbs. of pure sodium chloride per acre. At Cirencester, where the rainfall is 33·31 inches, the proportion of chlorine is 3·25 per million, which is equivalent to 40·3 lbs. of sodium chloride per acre. R. Warington, *Journ. Chem. Soc.* 1887, p. 502.

[2] Among the inorganic contents of rain and snow, fine terrestrial dust and spherules of iron, probably in part of cosmic origin, have been specially noted. See authorities cited *ante*, p. 68; A. von Lasaulx, as cited on p. 337. The organic matter of rain is revealed by the putrid smell which long-kept rain-water gives out.

[3] Angus Smith, 'Air and Rain,' p. 233.

[4] *Rivers Pollution Commission*, 6th Rep. p. 32.

Chemical and mineralogical changes due to rain-water.—In previous pages, it was pointed out that all rocks and minerals are, in varying degrees, porous and permeable by water, that probably no known substance can, under all conditions, resist solution in water, and that the subsequent solvent power of water is greatly increased by the solutions which it effects and carries with it in its progress through rocks (pp. 306, 307). The chemical work done by rain may be conveniently considered under the five heads of Oxidation, Deoxidation, Solution, Formation of Carbonates, and Hydration.

1. *Oxidation.*—The prominence of oxygen in rain-water, and its readiness to unite with any substance that can contain more of it, render oxidation a marked feature of the passage of rain over rocks. A thin oxidized pellicle is formed on the surface, and this, if not at once washed off, is thickened from inside until a crust is formed over the stone, while at the same time the common dark green or black colour of the original rock changes into a yellowish, brownish, or reddish hue. This process is simply a rusting of those ingredients which, like metallic iron, have no oxygen, or have not their full complement of it. The ferrous and manganous oxides so frequently found as constituents of minerals are specially liable to this change. In hornblende and augite, for example, one cause of weathering is the absorption of oxygen by the iron and the hydration of the resultant peroxide. Hence the yellow and brown sand into which rocks abounding in these minerals are apt to weather. Sulphides of the metals give rise to sulphates, and sometimes to the liberation of free sulphuric acid. Iron disulphide, for example, becomes copperas, which on oxidation of the iron, gives a precipitate of limonite, with the escape of free sulphuric acid.

2. *Deoxidation.*—Rain becomes a reducing agent by absorbing from the atmosphere and soil organic matter which, having an affinity for oxygen, decomposes peroxides and reduces them to protoxides. This change is especially noticeable among iron-oxides, as in the familiar white spots and veinings so common among red sandstones. These rocks are stained red by ferric oxide (hæmatite), which, reduced by decaying organic matter to ferrous oxide, is usually removed in solution as an organic salt or a carbonate. When the deoxidation takes place round a fragment of plant or animal, it usually extends as a circular spot; where water containing the organic matter permeates along a joint or other divisional plane, the

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[1] Senft, *Z. Deutsch. Geol. Ges.* xxiii. p. 665, xxvi. p. 954. This subject has been well treated in a paper by A A. Julien "On the Geological Action of the Humous Acids" (*Proc. Amer. Assoc.* xxviii. 1879, p. 311), to which further reference is made in later pages. See also his excellent paper on the decomposition of pyrites, *Ann. New York Acad. Sci.* vol. iv. (1888).

decoloration follows that line. Another common effect of the presence of organic matter is the reduction of sulphates to the state of sulphides. Gypsum is thus decomposed into sulphide of calcium, which in water readily gives calcium carbonate and sulphuretted hydrogen, and the latter by oxidation leaves a deposit of sulphur. Hence from original beds of gypsum, layers of limestone and sulphur have been formed, as in Sicily and elsewhere (p. 67).[1]

3. *Solution.*—A few minerals (halite, for example) are readily soluble in water without chemical change, and without the aid of any intermediate element; hence the copious brine-springs of salt regions. In the great majority of cases, however, solution is effected through the medium of carbonic acid or other re-agent. Limestone is soluble to the extent of about 1 part in 1000 of water saturated with carbonic acid. The solution and removal of lime from the mortar of a bridge or vault, and the deposit of the material so removed in stalactites and stalagmites (p. 365), likewise the rapid effacement of marble epitaphs in our churchyards, are instances of this solution. It has been shown that in the atmosphere of a large town, with abundant coal-smoke and rain, exposed inscriptions on marble become illegible in half a century. Pfaff determined that a slab of Solenhofen limestone, 2520 square millimetres in superficies, lost in two years, by the solvent action of rain, 0·180 gramme in weight, in three years 0·548, the original polish being replaced by a dull earthy surface on which fine cracks and incipient exfoliation began to appear. Taking the specific gravity of the stone at 2·6, the yearly loss of surface amounts to $\frac{1}{728}$ millimetre, so that a crag of such limestone would be lowered 1 metre in 72,800 years by the solvent action of rain.[2] J. G. Goodchild, from observations of dressed surfaces of Carboniferous limestone in the north of England, has inferred that these surfaces have been lowered at rates varying from one inch in 240 years to the same amount in 500 years.[3] Dolomite is much more feebly soluble than limestone. As rain-water attacks the carbonate of lime more readily than the carbonate of magnesia, the rock is apt to acquire a somewhat porous or carious texture, with a corresponding increase in the proportion of its magnesian carbonate. Eventually the latter carbonate is dissolved and redeposited in the pores of the rock, which then assumes a characteristic crystalline aspect. Among the sulphates, gypsum is the most important example of solution. It is dissolved in the proportion of about 1 part in 400 parts of water.

4. *Formation of Carbonates.*—Silicates of lime, potash, and soda, with the ferrous and manganous silicates which exist so abundantly in rocks, are attacked by rain-water containing carbonic acid, with the formation of carbonates of these bases and the liberation of silica. The felspars are thus decomposed. Their crystals lose their lustre and colour, becoming

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[1] The reducing action of organic acids is further described in Section iii.

[2] Pfaff, *Z. Deutsch. Geol. Ges.* xxiv. p. 405; and 'Allgemeine Geologie als exacte Wissenschaft,' p. 317. Roth, 'Allgemeine und Chem. Geol.' i. p. 70. Geikie, *Proc. Roy. Soc. Edin.* x. 1879-80, p. 518.

[3] *Geol. Mag.* 1890, p. 466.

dull and earthy on the outside, and the change advances inwards until the whole substance is converted into a soft pulverulent clay. In this decomposition the whole of the alkali, together with about two-thirds of the silica, is removed, leaving a hydrous aluminous silicate or kaolin behind. But the rapidity and completeness of the process vary greatly, especially in proportion to the abundance of carbonic acid. Where it advances with sufficient slowness, most of the silica, after the abstraction of the alkali, may be left behind. In the case of magnesian minerals (augite, hornblende, olivine, &c.) the silicates of magnesia and alumina, being less soluble, may remain as a dark brown or yellow clay, coloured by the oxidation of the iron, while the lime and alkalies are removed.[1] Evidence of the progress of these changes may be obtained even for some distance from the surface in many massive rocks. Diabase, basalt, diorite, and other crystalline rocks, which may appear to be quite fresh, will often reveal, by the effervescence produced when acid is dropped on their newly broken and seemingly undecomposed surfaces, that their silicates have been attacked by meteoric water and have been partially converted into carbonates.

5. *Hydration.*—Some anhydrous minerals, when exposed to the action of the atmosphere, absorb water (become hydrous), and may then be more prone to further change. Anhydrite becomes, by addition of water, gypsum, the change being accompanied by an increase of bulk to the extent of about 33 per cent. Local uplifts of the ground and crumpling or fracture of rocks may sometimes be caused by the hydration of subterranean beds of anhydrite (p. 298). Many substances on oxidizing likewise become hydrous. The oxidation of ferrous oxide in damp air gives rise to hydrous ferric oxide, with its characteristic yellow and brown colours on weathered surfaces.

Weathering.—This term expresses the general result of all kinds of meteoric action upon the superficial parts of rocks. As these changes almost invariably lead to disintegration of the surface, the word weathering has come to be naturally associated in the mind with a loosened crumbling condition of stone. But the influence of the atmospheric agents is not invariably to destroy the coherence of the integral particles of rocks. In some cases, stones harden on exposure. Certain sandy rocks, for example, like the "grey weathers" and scattered Tertiary blocks in the Ardennes, become under meteoric influence a kind of lustrous quartzite. In other cases, there may be more complex molecular rearrangements, such as those remarkable transformations to which Brewster first called attention in the case of artificial glass.[2] He showed that in thin films of decomposed glass, obtained from Nineveh and other ancient sites, concentric agate-like rings of devitrification are formed round isolated points, closely analogous to those above described as artificially produced by the action of heated alkaline waters (p. 309), and that groups of crystals or crystallites, "probably of silex," are developed from many independent points in the decomposing layer. Coloured films indicative of incipient decomposition have been observed on surfaces of glass exposed only to the air of the atmosphere for twenty or thirty years. Brilliantly iridescent films have been produced on the glass of windows exposed for not more than twenty years to the air and ammoniacal vapours of a stable.[1] That similar transformations take place in the natural silicates of rocks seems in the highest degree probable. They may form the earliest stages of the change to the usual opaque earthy decomposing crust, in which, of course, all trace of any structure developed in the preliminary weathering is lost.[2]

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[1] Roth, *op. cit.* i. p. 112.

[2] *Trans. Roy. Soc. Edin.* xxii. 607 ; xxiii. 193. See *ante*, p. 310.

In humid and temperate climates, weathering is mainly due to the combined influence of rain and sunshine. Saturated with rain-water, which dissolves more or less of any soluble constituents that may be present, and thereafter exposed to the desiccating and expanding influence of the warm rays of the sun, rock-surfaces are disintegrated, breaking up into angular fragments or crumbling into dust.[3] In high mountainous situations, as well as in lower regions where the temperature falls below the freezing-point in winter, weathering is in large measure caused by the action of frost (p. 413); in arid lands subject to great and rapid alternations of temperature, it may be mainly due to the strain of alternate expansion and contraction (p. 328) and the mechanical action of the wind (p. 329 *et seq.*) As the name denotes, weathering is dependent on meteorological conditions, and varies, even in the same rock, as these conditions change, but is likewise almost infinitely diversified according to the structure, texture, and composition of rocks.

Mere hardness or softness forms no sure index to the comparative power of a rock to resist weathering. Many granites, for instance, weather to clay, deep into their mass, while much softer limestones retain smooth, hard surfaces. Nor is the depth of the weathered surface any better guide to the relative rapidity of waste. A tolerably pure limestone may weather with little or no crust, and yet may be continually losing an appreciable portion of its surface by solution, while an igneous rock, like a diorite or basalt, may be encased in a thick decomposed crust and weather with extreme slowness. In the former case, the substance of the rock being removed in solution, few or no insoluble portions are left to mark the progress of decay, while in the igneous rock, the removal of but a comparatively small proportion causes disintegration, and the remaining insoluble parts are found as a crumbling crust. Impure limestone, however, yields a weathered crust of more or less insoluble particles. Hence, as we have already seen (p. 81) the relative purity of limestones may be roughly determined from their weathered surfaces, where, if they contain much sand, the grains will be seen projecting from the calcareous matrix; should they be very ferruginous, the yellow hydrous peroxide, or ochre, will be found as a powdery crust; or if they be fossiliferous, they will commonly present the fossils standing out in relief. An experienced fossil-collector will always carefully search weathered surfaces of limestone, for he often finds there, delicately picked out by the weather, minute and frail fossils, which are wholly invisible on the freshly broken stone. This difference arises from the crystalline calcite of the organic remains being less soluble than the more granular calcite in which these are imbedded. Limestones frequently assume a remarkable channelled rugose surface, with projecting knobs, ridges, and pinnacles especially developed in high bare tracts of ground (Karrenfelder).[1]

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[1] This fact has been observed by my friend Mr. P. Dudgeon, of Cargen, in an ill-ventilated cow-house, and I have seen the plates of glass removed from the windows. The process of decay in glass has been treated of in great detail by Mr. James Fowler, *Trans. Soc. Antiquaries*, xlvi. (1879), pp. 65-162.

[2] Reference may be made here to the liquid inclusions already alluded to as developed in felspar during the decomposition of gneiss, *ante*, p. 112.

[3] This action can be instructively imitated by boiling and drying shales in the manner described in Book V. Sect. vii.

Rocks liable to little chemical change are best fitted to resist weathering, provided their particles have sufficient cohesion to withstand the mechanical processes of disintegration.[2] Siliceous sandstones offer excellent examples of this permanence. Consisting mainly of the durable minerable quartz, they are sometimes able so to withstand decay that buildings made of them still retain, after the lapse of centuries, the chisel-marks of the builders. Many sandstones, however, contain argillaceous, calcareous, or ferruginous concretions which weather more rapidly than the surrounding rock, and cause it to assume a honeycombed surface; others are full of a diffused cement (clay, lime, iron) the decay of which makes the rock crumble down into sand. In sandstones, as indeed in most stratified rocks, there is a tendency towards more rapid weathering along the planes of stratification, so that the stratified

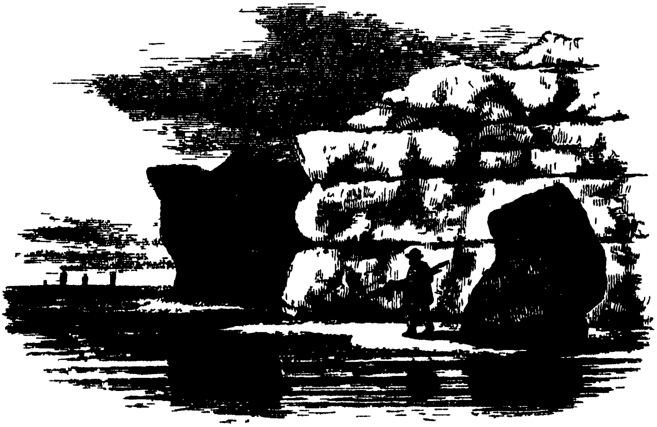

Fig. 92.—Weathered sandstone cliffs showing irregular honeycombing and weathering along planes of stratification (B.)

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[1] Heim, *Jahrb. Schweiz. Alpenclubs*, xiii. (1878).

[2] On weathering of building-stones, see *Proc. Roy. Soc. Edin.* 1879-80, p. 518. Julien, *Trans. New York Acad. Sci.* Jan. 1883. W. Wallace, *Proc. Phil. Soc. Glas.* xiv. (1882-3), p. 22.

structure is brought out very clearly on natural cliffs (Fig. 92). In many ferruginous sandstones and clay ironstones, successive yellow or brown zones or shells may be traced inward from the surface, frequently due to changes of the ferrous carbonate into limonite, the interior remaining still fresh. In many prismatic massive rocks (basalt, diorite, &c.), segments of the prisms weather into spheroids, in which successive weathered rings form crusts like the concentric coats of an onion (Figs. 93, 94). Where one of these rocks has been intruded as a dyke, it sometimes decomposes to a considerable depth into a mass of brown ferruginous balls in a surrounding sandy matrix—the whole having at first a resemblance to a conglomerate made of rolled and transported fragments (Fig. 95).

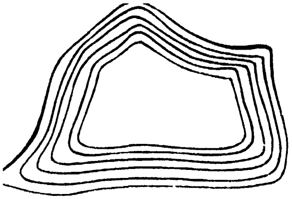

Fig 93 —Rings of Weathering

No rock presents greater variety of weathering than granite. Some remarkably durable kinds only yield slowly at the edges of the joints, the separated masses gradually assuming the form of rounded blocks like water-worn boulders. Other kinds decompose to a depth of 50 feet or more, and can be dug out with a spade. In Cornwall and

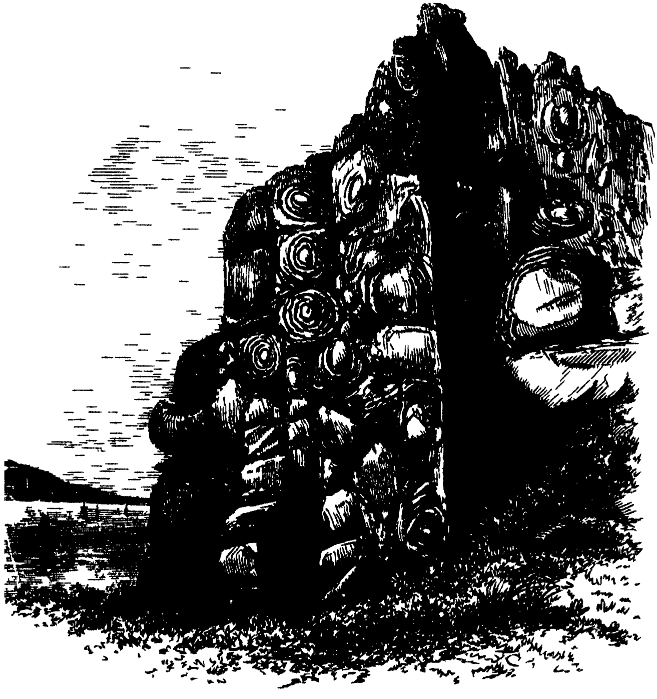

Fig 94 —Spheroidal Weathering of Dolerite, North Queensferry

Devon, the kaolin from the rotted granite, largely extracted for pottery purposes, is found down to a depth of occasionally 600 feet. That what appears to be mere loose sand and clay is really rock decomposed *in situ*, is proved by the quartz-veins and bands of schorl-rock which ascend from the solid rock (*a*, Fig. 96) into the friable part (*b*), and by the entire agreement in structure between the two portions. Here and there, kernels of still undecomposed granite may be seen (as at *c c* in Fig. 97), surrounded by thoroughly decayed material, and, like the solid cores of basalt above-mentioned, presenting a deceptive resemblance to accumulations of transported materials. There can be no doubt that the granite boulders, so abundantly transported by the ice-sheets and glaciers of the Ice Age, originated in great measure in this way. Owing to its numerous joints, granite occasionally weathers into forms that resemble ruined walls. Large slabs, each defined by joint planes, weather out one above another like tiers of masonry (Fig. 98), until, loosened by disintegration, they slip off and expose lower parts of the rock to the same influences. Here and there, a separate block becomes so poised that it may be readily moved to and fro by the hand, as in the so-called "rocking-stones" of granite districts. As the disintegration varies with local differences in durability, some portions weather into cavities, others into prominences, often with a singularly artificial appearance, as in the "rock basins" (Fig. 99) and "tors" (Fig. 98) of the south-west of England. The ruin-like weathering of dolomite gives rise in the Cevennes to some singularly picturesque scenery.

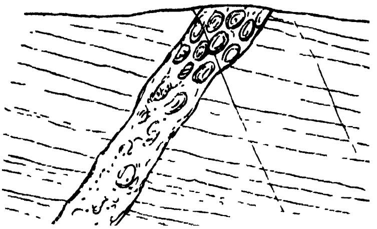

Fig. 95.—Felsite Dyke weathering into spheroids, Cornwall (*B.*)

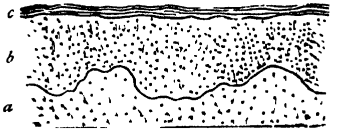

Fig. 96.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, vegetable soil

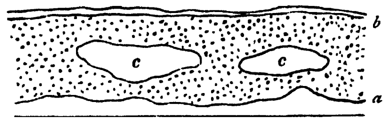

Fig. 97.—Decomposition of Granite. *a*, Solid granite; *b*, decomposed granite; *c*, *c*, kernels of still undecomposed granite.

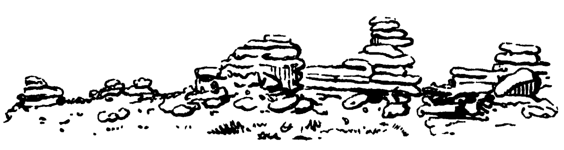

Fig. 98.—Weathering of Granite along its joints (*B.*)

To the influence of weathering, many of the most familiar minor contours of the land may be traced. So characteristic are these forms for particular kinds of rock, that they serve as a means of recognising them even from a distance. (Book VII.)

In countries which have not been under water for a vast lapse of time, and where consequently the superficial rocks have been continuously exposed to subaerial disintegration, thick accumulations of "rotted rock" are found on the surface. The extent of this change is sometimes impressively marked in areas of calcareous rocks. Limestone being mostly soluble, its surface is continually dissolved by rain, while the insoluble portions remain behind as a slowly increasing deposit. In regions which, possessing the necessary conditions of climate, have been for a long period unsubmerged, tracts of limestone, unprotected by glacial or other accumulations, are found to be covered with a red loam or earth. This characteristic layer occurs on a limited scale over the chalk of the south-east of England, where, with its abundant flints, it lies as the undissolved ferruginous residue of the chalk that has been removed to a depth of many yards. It occurs likewise in swallow-holes and other passages dissolved out of calcareous masses, and forms the well-known red earth of bone caves. In south-eastern Europe it plays an important part among superficial deposits, being extensively developed over the limestone districts, especially in Istria and Dalmatia, where it is known as the ferruginous red earth or *terra rossa*.[1]

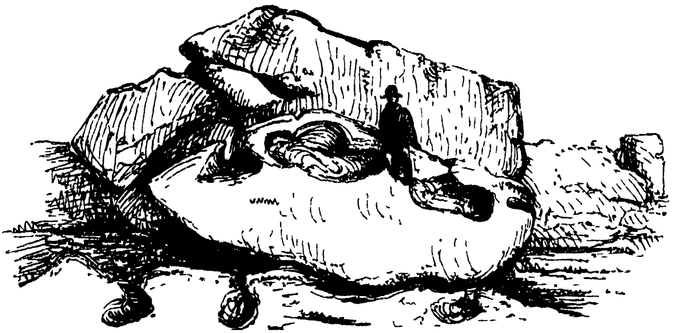

Fig. 99.—The "Kettle and Pans," St. Mary, Scilly; cavities weathered out of Granite (*B.*)

Other remarkable examples of similar subaerial waste have been specially noticed among crystalline schists and eruptive rocks. In Brazil, it has been remarked with astonishment that the crystalline rocks are sometimes decayed to a depth of more than 300 feet.[2] In Massachusetts,

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[1] On the origin of "Terra Rossa," see M. Neumayr, *Verhandl. Geol. Reichsanst.* 1875, p. 50; Th. Fuchs, *op. cit.* p. 194; E. von Mojsisovics, *Jahrb. Geol. Reichsanst.* xxx. (1880), p. 210; E. Tietze, *op. cit.* xxx. (1880), p. 729: Lorenz, *Verh. Geol. Reichs.* 1881, p. 81; C. de Georgi, *Boll. Com. Geol. Ital.* vii. p. 294. It is included among the ferruginous deposits by Stoppani ('Corso di Geologia,' iii. p. 534). Neumayr shows that it is of various ages; in the Karst it encloses Miocene mammals.

[2] Liais, 'Géologie du Brésil,' p. 2. *Ann. des Mines*, 7me sér. viii. p. 698. T. Belt, 'Naturalist in Nicaragua' (1874), p. 86. T. Sterry Hunt, *Amer. Journ. Sci.* 3rd ser. vii. p. 60; xxvi. (1883), p. 196; *Geol. Mag.* 1883, p. 310; *American Naturalist*, ix. (1875), p. 471. This writer dwells especially on the great geological antiquity of the weathered crust. On the secular rock-weathering of the Swedish mountains see Nathorst, *Geol. Fören. Stockholm. Förhand.* 1879, iv. No. 13.

Pennsylvania, and generally in the middle and southern Atlantic States of North America, the depth of disintegration appears gradually to increase southward from the limits where the country has been "glaciated" by ice-sheets during the Glacial Period.[1] In central Asia, a similar superficial decay has been observed.[2] Dr. Sterry Hunt has specially drawn attention to the geological importance of this prolonged disintegration *in situ.* Mr. Pumpelly points out that, as masses of decomposed rock may be observed to a depth of over 100 feet, the surface of the still solid rock underneath presents ridges and hollows, succeeding each other according to varying durability under the influence of percolating carbonated water. In this kind of weathering, where erosion does not come into play, it is evident that the resulting topography must, in some important respects, differ from that of an ordinary surface of superficial denudation. In particular, rock-basins may be gradually eaten out of the solid rock. These will remain full of the decomposed material, but any subsequent action, such as that of glacier-ice, which could scoop out the detritus, would leave the basins and their intervening ridges exposed.[3]

Formation of Soil.—On level surfaces of rock the weathered crust may remain with comparatively little rearrangement until plants take root on it, and by their decay supply organic matter to the decomposed layer, which eventually becomes what we term "vegetable soil." Animals also furnish a smaller proportion of organic ingredients. Though the character of soil depends primarily on the nature of the rock out of which it has been formed, its fertility largely depends on the commingling of decayed animal and vegetable matter with decomposed rock.

A gradation may be traced from the soil downwards into what is termed the "subsoil," and thence into the solid rock underneath (Fig. 100). Between soil and subsoil a marked difference in colour is often observable, the former being yellow or brown, when the latter is blue, grey, red, or other colour of the rock beneath.[4] This contrast, evidently due to oxidation and hydration, especially of the iron, extends downwards as far as the

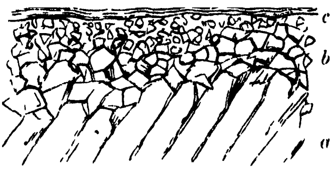

Fig. 100.—Section showing the upward passage of Rock (*a*) into Subsoil (*b*), and thence into Vegetable Soil (*c*).

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[1] I. C. Russell, *Bull. U.S. Geol. Survey*, No. 52 (1889), p. 12 *et seq.* There is a useful bibliography of papers on the subaerial decay of rocks appended to this essay. See also W. O. Crosby, *Proc. Nat. Hist. Soc. Boston*, xxiii. p. 219.

[2] On a smaller scale it is also to be noted in the granite and killas (phyllite) of Cornwall and Devon which, not having suffered from the abrading action of the ice of the Glacial Period, show a deep cover of rotted rock, and afford some indication of what may have been elsewhere the condition of Britain before the period of glaciation. The sea-cliffs along the north coast of Cornwall expose instructive sections of the deep upper decomposed, and of the lower blue solid killas, with the remarkably uneven boundary along which they pass into each other.

[3] Pumpelly, *Amer. Journ. Sci.* 3rd ser. xviii. 136; L. S. Burbank, *Proc. Bost. Nat. Hist. Soc.* xvi. (1874), part 2, p. 150; also *postea*, p. 431.

[4] Deceptive appearances of a break between the soil or subsoil and what lies beneath are

subsoil is opened up by rootlets and fibres to the ready descent of rain-water. The yellowing of the subsoil may even occasionally be noticed around some stray rootlet which has struck down further than the rest, below the general lower limit of the soil (*postea*, p. 473).

Mr. Darwin observed many years ago that a layer of soil, three inches in depth, had grown above a layer of burnt marl spread over the land fifteen years previously; also that in another example, a similar layer had, as it were, sunk beneath the soil, to a depth of twelve or thirteen inches in eighty years. He connected these facts with the work of the common earth-worm, and concluded that the fine loam which had grown above these original superficial layers had been carried up to the surface, and had been voided there in the familiar form of worm-castings.[1] This action of the earth-worm is doubtless highly important, but, as Richthofen has pointed out, we have to take also into account the gradual augmentation of level due to the daily deposit of dust (*ante*, p. 331, and *postea*, p. 473).

Soil being composed mainly of inorganic, and to a slight extent of organic materials, the proportion between these two elements is a question of high economic importance. With regard to the organic matter, it is the experience of practical agriculturists in Britain that oats and rye will grow upon a soil with 1½ per cent of organic matter, but that wheat requires from 4 to 8 per cent.[2] To a geologist, this organic matter has much interest, as the source of most of the carbonic acid, with which so wide a series of changes is worked by subterranean water. The inorganic portion of soil, or still undissolved residue of the original surface-rock, varies from a loose open substance with 90 per cent or more of sand, to a stiff, cold, retentive material with more than 90 per cent of clay. When this sand and clay are more equally mixed they form a "loam."[3]

Reference has just been made to the thick accumulation of rock decomposed *in situ* observable in certain regions which, having been above the sea for a lengthened period, have been long exposed to the action of weathering. Where this action has been supplemented by that of rain, widespread formations of loam and earth have been gathered together. These are well illustrated by the "brick-earth," "head," and "rain-wash" of the south of England—earthy deposits, with angular stones, derived from the subaerial waste of the rocks of the neighbourhood.[4]

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sometimes produced by this means. See W. Whitaker, *Q. J. Geol. Soc.* xxxiii. p. 122. E. Van den Broeck, *Mém. Couronn. Acad.* Brussels, 1881.

[1] *Geol. Trans.* v. 1840, p. 505; and his more recent researches in his volume on 'Vegetable Mould.' See also C. Reid, *Geol. Mag.* 1884, p. 165.

[2] Johnston's 'Elements of Agricultural Chemistry,' p. 80.

[3] For measurements of the permeability of soils, see Houdaille and Semichow, *Compt. rend.* cxv. (1892), p. 1015.

[4] Godwin-Austen, *Q. J. Geol. Soc.* vi. p. 94, vii. p. 121; Foster and Topley, *op. cit.* xxi. p. 446. The vast extent of some superficial formations, like the "loess" above referred to (p. 332), has often suggested submergence below the sea. But when, instead of marine organisms, only terrestrial, fluviatile, or lacustrine remains occur in them, as in the brick-earths and loess, the idea of marine submergence cannot be entertained. The remarkable

2. **Mechanical Action.**—Besides chemically corroding rocks and thereby loosening the cohesion of their particles, rain acts mechanically by washing off these particles, which are held in suspension in the little rain-runnels or are pushed by them along the surface. The amount and rapidity of this action do not depend merely on the annual quantity of rain. A comparatively large rainfall may be so equably distributed through a year or season as to produce less change than may be caused by a few heavy rain-storms which, though inferior in total amount of precipitated moisture, descend rapidly in great volume. Such copious rains, by deluging the surface of a country and rapidly flooding its water-courses, may transport in a few hours an enormous amount of sand and mud to lower levels. Another feature to be kept in view is the angle of declivity: the same amount of rain will perform vastly more mechanical work if it can swiftly descend a steep slope, than if it has to move tardily over a gentle one.

Removal and Renewal of Soil.—Élie de Beaumont drew attention to what appeared to be proofs of the permanence or long duration of the layer of vegetable soil.[1] But the cases cited by him are not inconsistent with a belief that the doctrine of the persistence of the soil is true rather of the layer as a whole, than of its individual particles.[2] Were there no provision for its renewal, soil would comparatively soon be exhausted, and would cease to support the same vegetation. This result, indeed, occurs partially, especially on flat lands, but would be far more widespread were it not that rain, gradually washing off the upper part of the soil, exposes what lies beneath to further disintegration. This removal takes place even on grass-covered surfaces, through the agency of earth-worms, by which fine particles of loam are brought up and exposed to the air, to be dried and blown away by wind, or washed down by rain. The lower limit of the layer of soil is thus made to travel downward into the subsoil, which in turn advances into the underlying rock. As Hutton long ago insisted, the superficial covering of soil is constantly, though slowly, travelling to the sea.[3] In this ceaseless transport, rain acts as the great carrying agent. The particles of rock and of soil are, step by step, moved downward over the face of the land, till they reach the nearest brook or river, whence their seaward progress may be rapid. A heavy rain discolours the water-courses of a country, because it loads them with the fine débris which it removes from the general surface of the land. In this way, rain serves as the means whereby the work of other disintegrating forces is made conducive to the general degradation of the land. The decomposed crust produced by weathering, which would otherwise accumulate over the solid rock, and in some measure protect it from decay, is removed by rain, and a fresh surface is thereby laid bare to further decomposition.

"tundras" or steppes of Siberia, and the "black earth" of Russia, are examples of such extensive formations, which are certainly not of marine origin, but point to long-continued emergence above the sea. See Murchison, Keyserling, and De Verneuil's 'Geology of Russia.' Belt, *Q. J. Geol. Soc.* xxx. p. 490; also *postea*, p. 478.

[1] 'Leçons de Géologie pratique,' i. p. 140.

[2] Geikie, *Trans. Geol. Soc. Glasgow*, iii. p. 170.

[3] 'Theory of the Earth,' Part II. chaps. v. vi.

Movement of Soil-cap.—In some countries, where the ground is covered with a thick spongy mass of vegetation exposed to considerable variation of temperature and moisture, appearances have been observed of an extensive slipping of the layer of soil to lower levels, bearing with it whatever may be growing or lying upon it. Such are the so-called "stone-rivers" of the Falkland Islands, and the superficial débris of certain parts of the west coast of Patagonia.[1] In Western Europe, slight indications of a similar movement may often be noticed on the sides of hills or valleys.

Unequal Erosive Action of Rain.—While the result of rain action is the general lowering of the level of the land, this process necessarily advances very unequally in different places. On flat ground, the waste may be quite inappreciable, except after long intervals and by the most accurate measurements, or it may even give place to deposition, the fine detritus washed off the slopes being spread out, so as actually to heighten the alluvial surface. In numerous localities, great variations in the rate of erosion by rain may be observed. Thus, from the pitted, channelled ground lying immediately under the drip of the eaves of a house, fragments of stone and gravel stand up prominently, because the earth around and above them has been washed away by the falling drops, and because, being hard, they resist the erosive action and screen the earth below them. On a larger scale the same kind of operation may be noticed in districts of conglomerate, where the larger blocks, serving as a protection to the rock underneath, come to form, as it were, the capitals of slowly-

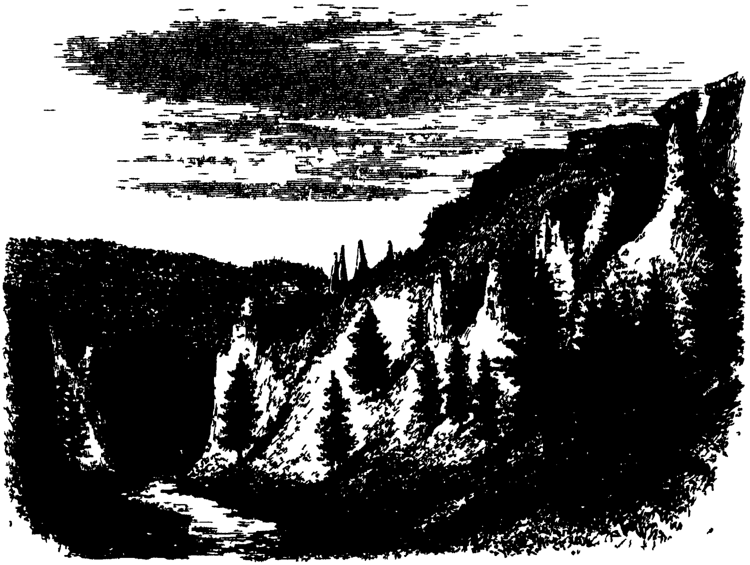

Fig. 101.—Rain-eroded pillars of Old Red Conglomerate, Fochabers.

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[1] Wyville Thomson's 'Atlantic,' vol. ii. p. 245. R. W. Coppinger, *Q. J. Geol. Soc.* 1881, p. 348. See *postea*, under "Landslips," p. 370.

deepening columns of rock (Fig. 101). In certain valleys of the Alps a stony clay is cut by the rain into pillars, each of which is protected by, and indeed owes its existence to, a large block of stone which lay originally in the heart of the mass (Fig. 102). These columns, or "earth-pillars," are of all heights, according to the original positions of the stones. More colossal examples have been described by Hayden from the conglomerates of Colorado.

There are instances, however, where the disintegration has been so complete that only a few scattered fragments remain of a once extensive stratum, and where it may not be easy to realise that these fragments are not transported boulders. In Dorsetshire and Wiltshire, for example, the surface of the country is in some parts so thickly strewn with fragments of sandstone and conglomerate "that a person may almost leap from one stone to another without touching the ground. The stones are frequently of considerable size, many being four or five yards across, and about four feet thick."[1] They are found lying abundantly on the Chalk, suggestive

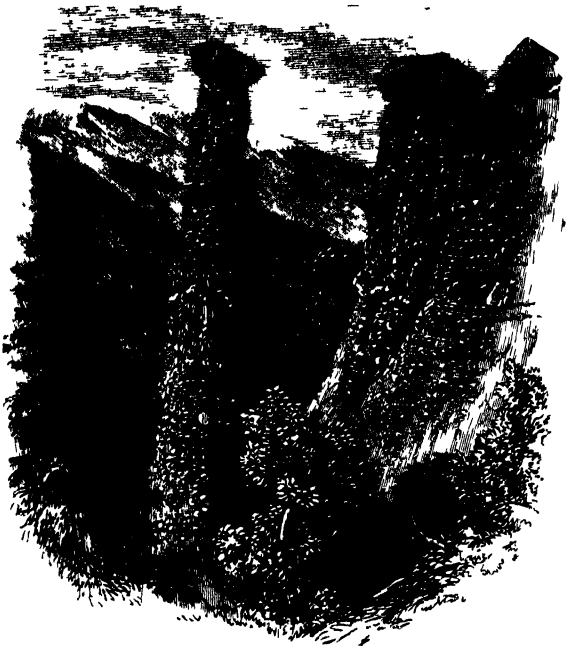

Fig 102 —Earth-pillars left by the weathering of moraine-stuff, Tyrol.

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[1] They have been used for the huge blocks of which Stonehenge and other of the so-called Druidical circles have been constructed, hence they have been termed Druid Stones Other names are Sarsen Stones (supposed to indicate that their accumulation has been popularly ascribed to the Saracens), and Grey Wethers, from their resemblance in the distance to flocks

at first of some former agent of transport by which they were brought from a distance. They are now, however, generally admitted to be simply fragments of some of the sandy Tertiary strata which once covered the districts where they occur. While the softer portions of these strata have been carried away, the harder parts (their hardness perhaps increasing by exposure) have remained behind as "Grey Wethers," and have subsequently suffered from the inevitable splitting and crumbling action of the weather. Similar blocks of quartzite and conglomerate, referable to the disintegration of Lower Tertiary beds *in situ*, are traceable in the north-east of France up into the Ardennes, showing that the Tertiary deposits of the Paris basin once had a much wider extension than they now possess.[1] On a far grander scale, the apparent caprice of general subaerial disintegration is exhibited among the "buttes" and "bad lands" of Wyoming and the neighbouring territories of North America. Colossal pyramids, barred horizontally by level lines of stratification, rise up one after another far out into the plains, which were once covered by a continuous sheet of the formations whereof these detached outliers are only fragments.

As a consequence of this inequality in the rate of waste, depending on so many conditions, notably upon declivity, amount and heaviness of rain, lithological texture and composition, and geological structure, great varieties of contour are worked out upon the land. A survey of this department of geological activity shows, indeed, that the unequal wasting by rain has in large measure produced the details of relief on the present surface of the continents, those tracts where the destruction has been greatest forming hollows and valleys, others, where it has been less, rising into ridges and hills. Even the minuter features of crag and pinnacle may be referred to a similar origin. (Book VII.)

§ 2. Underground Water.

A great part of the rain that falls on land, sinks into the ground and apparently disappears; the rest, flowing off into runnels, brooks, and rivers, moves downward to the sea. It is most convenient to follow first the course of the subterranean water.

All rocks being more or less porous, and traversed by abundant joints and cracks (p. 306), it results that from the bed of the ocean, from the bottoms of lakes and rivers, as well as from the general surface of the land, water is continually filtering downward into the rocks beneath. To what depth this descent of surface-water may go, is not known. As stated in a former section, it may reach as far as the intensely heated interior of the planet, for, as the already quoted researches of Daubrée have shown, capillary water can penetrate rocks even against a high counter-pressure of vapour (*ante*, p. 306). Probably the depth to which

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of (wether) sheep. See *Descriptive Catalogue of Rock Specimens in Jermyn Street Museum*, 3rd ed.; Prestwich, *Q. J. Geol. Soc.* x. p. 123; Whitaker, *Geological Survey Memoir on parts of Middlesex*, &c., p. 71.

[1] Barrois, *Ann. Soc. Géol. du Nord*, vi. p. 366.

the water descends varies indefinitely according to the varying nature of the rocky crust. Some shallow mines are practically quite dry, others of great depth require large pumping engines to keep them from being flooded by the water that pours into them from the surrounding rocks. Yet, as a rule, the upper layers of rock in the earth's crust are fuller of moisture than those deeper down.

Underground Circulation and Ascent of Springs.—The water which sinks below ground is not permanently removed from the surface, though there must be a slight loss due to absorption and chemical alteration of rocks. Finding its way through joints, fissures, or other divisional planes, it issues once more at the surface in springs. This may happen either by continuous descent to the point of outflow, or by hydrostatic pressure. In the former case, rain-water, sinking underneath, flows along a subterranean channel until, when that channel is cut by a valley or other depression of the ground, the water emerges again to daylight. Thus, in a district having a simple geological structure (as in Fig. 103), a sandy porous stratum (*d*), through which water readily finds its way, may rest on a less easily permeable clay (*e*), followed underneath by a second sandy pervious bed (*c*), resting as before upon comparatively impervious[1] strata (*a*). Rain falling upon the upper sandy stratum (*d*), will sink through it to the surface of the clay (*e*), along which it will flow until it issues either as springs, or in a general line of wetness along the side of the valley (*b*). The second sandy bed (*c*) will serve as a reservoir of subterranean water so long as it remains below the surface, but any valley cutting down below its base will drain it.

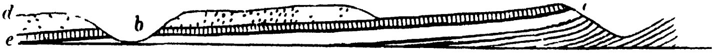

Fig. 103.—Simple or Surface Springs.

Except, however, in districts of gently inclined and unbroken strata, springs are more usually of the second class, where the water has descended to a greater or less distance, and has risen again to the surface in fissures, as in so many syphons. Lines of joint and fault afford ready channels for subterranean drainage (Fig. 104). Powerful faults which bring different kinds of rock against each other (as *a* and *g* are by the fault *f* in Fig. 104) are frequently marked at the surface by copious

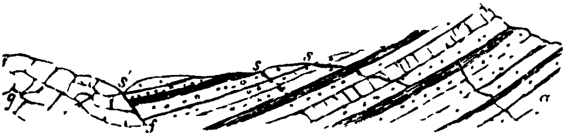

Fig. 104. -Deep-seated Springs (*s*, *s'*) rising through joints and a fault (*f*)

springs. So complex is the network of divisional planes by which rocks are traversed, that water may often follow a most labyrinthine course before it completes its underground circulation (Fig. 105). In countries with a sufficient rainfall, rocks are saturated with water below a certain limit termed the *water-level.* Owing to varying structure, and relative capacity for water among rocks, this line is not strictly horizontal, like that of the surface of a lake. Moreover, it is liable to rise and fall according as the seasons are wet or dry. In some places it lies quite near, in others far below, the surface. A well is an artificial hole dug down below the water-level, so that the water may percolate into it. Hence, when the water-level happens to be at a small depth, wells are shallow; when at a greater depth, they require to be deeper.

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[1] This term *impervious* must evidently be used in a relative and not in an absolute sense. A stiff clay is practically impervious to the trickle of underground water; hence its employment as a material for puddling (that is, making water-tight) canals and reservoirs. But it contains abundant interstitial water, on which, indeed, its characteristic plasticity depends.

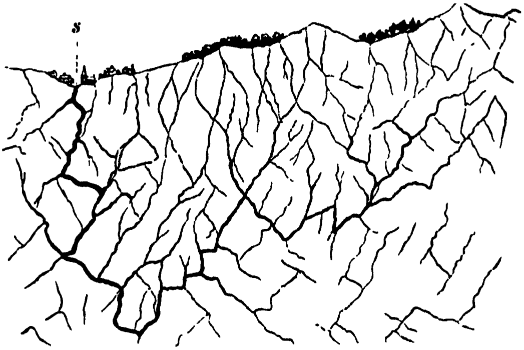

Fig. 105.—Intricate subterranean course of percolating water.

Since rocks vary greatly in porosity, some contain far more water than others. It often happens that, percolating along some porous bed, subterranean water finds its way downward until it passes under some more impervious rock. Hindered in its progress, it accumulates in the porous bed, from which it may be able to find its way up to the surface again only by a tedious circuitous passage. If, however, a bore-hole be sunk through the upper impervious bed down to the water-charged stratum below, the water will avail itself of this artificial channel of escape, and will rise in the hole, or even gush out as a *jet d'eau* above ground. Wells of this kind are now largely employed. They bear the name of *Artesian*, from the old province of Artois in France, where they have long been in use[1] (Fig. 106).

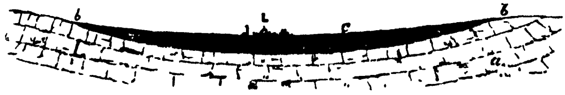

Fig. 106.—Diagram illustrative of the theory of Artesian Wells.
a, b, Lower water-bearing rocks, covered by an impervious series (*c*), through which, at L and elsewhere, borings are made to the water-level beneath.

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[1] See Prestwich *Q. J. Geol. Soc.* xxviii. p. lvii., and the references there given. One of the best recent essays on the subject of Artesian Wells is that by Professor T. C. Chamberlin in the 5th Annual Report of the U.S. Geol. Survey (1883-84), p. 131.

That the water really circulates underground, and passes not merely through the pores of the rocks, but in crevices and tunnels, which it has no doubt to a large extent opened for itself along natural joints and fissures, is proved by the occasional rise of leaves, twigs, and even live fish, in the shaft of an Artesian well. Such testimony is particularly striking when found in districts without surface-waters, and even perhaps with little or no rain. It has been met with, for instance, in sinking wells in some of the sandy deserts on the southern borders of Algeria.[1] In these and similar cases, it is clear that the water may, and sometimes does, travel for many leagues underground, away from the district where it fell as rain or snow, or where it leaked from the bed of a river or lake.

The temperature of springs affords a convenient, but not always quite reliable indication of the relative depth from which they have risen. Some springs are just one degree or less above the temperature of ice (C. 0°, Fahr. 32°). Others, in volcanic districts, issue with the temperature of boiling water (C. 100°, Fahr. 212°). Between these two extremes every degree may be registered. Very cold springs may be regarded as probably deriving their supply from cold or snow-covered mountains. Certain exceptional cases, however, occur, where, owing to the subsidence of the cold winter air into caverns (*glacières*), ice is formed which is not wholly melted even though the summer temperature of the caves may be above freezing-point. Water issuing from these ice-caves is of course cold.[2] On the other hand, springs whose temperature is higher than the mean temperature of the places at which they emerge must have been warmed by the internal heat of the earth. These are termed *Thermal Springs.*[3] The hottest springs are found in volcanic districts (see p. 235). But even at a great distance from any active volcano, springs rise with a temperature of 120° Fahr. (which is that of the Bath springs) or even more. These have probably ascended from a great depth. If we could assume a progressive increase of 1° Fahr. of subterranean heat for every 60 feet of descent, the water at 120°, issuing at a locality whose ordinary temperature is 50°, should have been down at least 4200 feet below the surface. But from what has been already stated (p. 51) regarding the irregular stratification of temperature within the earth's crust, such estimates of the probable depth of the sources of springs are not quite reliable. The source of heat in these cases may be some crushing of the crust or ascent of heated matter from underneath, which does not, however, produce volcanic phenomena.

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[1] Desor, *Bull. Soc. Sci. Nat. Neufchâtel*, 1864. On the hydrology of the Sahara consult G. Rolland, *Assoc. Française*, 1880, p. 547. Tchihatchef, *Brit. Assoc.* 1882, p. 356. Choisy, 'Documents relatifs à la Mission dirigée au Sud de l'Algérie.' Paris, 1890.

[2] A remarkable example of a glacière is that of Dobschau, in Hungary, of which an account, with a series of interesting drawings, was published in 1874 by Dr. J. A. Krenner, keeper of the national museum in Buda-Pesth. See also Murchison, Keyserling, and De Verneuil, 'Geology of Russia.' Thury, *Biblioth. Univ.* Geneva, 1861. Browne, 'Ice-Caves in France and Switzerland,' 1865. Fifty-six of these caves are known in the Alps, some in the Jura, and many elsewhere.

[3] Studer points out that some springs which are thermal in high latitudes or at great elevations, would be termed cold springs near the equator, and, consequently, that springs having a lower temperature than that of the inter-tropical zone, that is from C. 0° to 30° (Fahr. 32°-84°), should be called "relative," those which surpass that limit (C. 30°-100°) "absolute," and he gives a series illustrative of each group: 'Physikalische Geographie,' ii. (1847), p. 49. For volcanic thermal springs see *ante*, p. 235, and *postea*, p. 363.

1. **Chemical Action.**—Every spring, even the clearest and most sparkling, contains dissolved gases, also solid matter abstracted from the soils and rocks which it has traversed. The gases include those absorbed by rain from the atmosphere (p. 341), also carbon-dioxide supplied by decomposing organic matter in the soil, sulphuretted hydrogen, and marsh-gas or other hydrocarbon derived from decompositions within the crust. The solid constituents consist partly of organic, but chiefly of mineral matter. Where spring-water has been derived from an area covered with ordinary humus, organic matter is always present in it. Organic acids are abstracted from the soil by descending water, and these, before they are oxidized into carbonic acid, are effective in decomposing minerals and forming soluble salts (p. 343). The mineral matter of spring-water consists principally of carbonates of calcium, magnesium, and sodium, sulphates of calcium and sodium, and chloride of sodium, with minute traces of silica, phosphates, nitrates, &c. The nature and amount of mineral impregnation depend, on the one hand, upon the chemical energy of the water, and on the other, upon the composition of the rocks.

Various sources of augmentation of its chemical energy are available for subterranean water. (1) The abundant organic matter in the soil partially abstracts oxygen from the water, but supplies organic acids, especially carbonic acid. In so far as the water carries down from the soil any oxidizable organic substance, its action must be to reduce oxides (p. 343). Ordinary vegetable soil possesses the power of removing from permeating water potash, silica, phosphoric acid, ammonia, and organic matter, elements which had been already in great measure abstracted from it by living vegetation, and which are again ready to be taken up by the same organic agents. (2) Carbon-dioxide is here and there largely evolved within the earth's crust, especially in regions of extinct or dormant volcanoes. Subterranean water coming in the way of this gas dissolves it, and thereby obtains increased solvent power. (3) The capacity of water for dissolving mineral substances is augmented by increase of temperature (*ante*, p. 307). It is conceivable that cold springs, containing a large percentage of mineral solutions, may have acquired this impregnation at a great depth and at a higher temperature. As a rule, however, thermal water, as it cools, deposits its dissolved minerals on the walls of the fissures up which it ascends. Hence, no doubt, the successive layers in mineral veins. (4) Pressure likewise raises the solvent power of water (p. 307). (5) Some of the solutions, due to decompositions effected by the water, increase its ability to accomplish further decompositions (p. 310). Thus the alkaline carbonates, which are among the earliest products, enable it to dissolve silica and decompose silicates. These carbonates likewise promote the decomposition of some sulphates and chlorides. Calcium-carbonate, which is found in the water of most springs, is the result of decomposition, and by its presence leads to the further disintegration of various minerals. "Carbonic acid, bicarbonate of lime, and the alkaline carbonates bring about most of the decompositions and changes in the mineral kingdom. It is a matter of great importance to find that the same substances which give rise to so many decompositions in the mineral kingdom are the chief ingredients in the waters."[1]

The nature of the changes effected by the percolation of water through subterranean rocks will be best understood from an examination of the composition of spring-water. Springs may be conveniently, though not very scientifically, grouped into two classes: 1st, Common springs, such as are fit for ordinary domestic purposes, and 2nd, mineral springs, in which the proportions of dissolved mineral matter are so much higher as to remove the water from the usual potable kinds.

1. Common Springs possess a temperature not higher but frequently lower than that of the localities at which they rise, and ordinarily contain, besides atmospheric air and its gases, calcium-carbonate and sulphate, common salt, with chlorides of calcium and magnesium, and sometimes organic matter. The amount of dissolved mineral contents in ordinary drinking water does not exceed 0·5, or at most 1·0 gramme per litre; the best waters contain less. The amount of organic matter should not exceed from 0·005 to 0·01 gramme per litre in wholesome drinking water.[2] Spring-water containing a very minute percentage of mineral matter, or in which this matter, even if in more considerable quantity, consists chiefly of alkaline salts, dissolves common soap readily, and is known in domestic economy as "soft" water. Where, on the other hand, the salts in solution are calcic or magnesic carbonates, sulphates, or chlorides, they decompose soap, forming with its fatty acids insoluble compounds which appear in the familiar white curdy precipitate. Such water is termed "hard." Where the hardness is due to the presence of bicarbonates it disappears on boiling, owing to the loss of carbonic acid and the consequent precipitation of the insoluble carbonate, while in the case of sulphates and chlorides no such change takes place.

The extensive investigations carried on by the Rivers Pollution Commission in Britain have thrown much light on the relation between the amount of mineral matter in solution in springs and wells, and the character of the underlying rock. The following table of analyses of waters from different kinds of rocks gives a summary of results obtained—

	No. of Analyses.	Mean amount of Solid Contents in 10,000 Parts of Water.
1. Fluviomarine, Drift and Gravel	10	6·132
2. Chalk	30	2·984
3. Hastings Sand and Greensands	19	3·005
4. Oolites	35	3·033
5. Lias	7	3·641
6. New Red Sandstone	15	2·869
7. Magnesian Limestone	1	6·652
8. Coal-Measures	14	2·430
9. Yoredale beds and Millstone-Grit	8	1·773
10. Mountain Limestone	13	3·206
11. Devonian and Old Red Sandstone	32	2·506
12. Silurian	15	1·233
13. Granite and Gneiss	8	0·594

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[1] Bischof, 'Chem. Geol.' i. p. 17.

[2] Dr. B. H. Paul in Watts' 'Dict. Chem.' v. p. 1022.

From this table it is evident how greatly the proportion of dissolved mineral substance augments in those waters which rise in calcareous tracts, and how it correspondingly sinks in those where the rocks are mainly siliceous. The maximum percentage in group No. 13 was less than 1 part in every 10,000 of water, the minimum being 0·140 from granite. In No. 1, on the contrary, the maximum was 22·524, in No. 6 it was 7·426, and in No. 10 it was 9·850.[1]

2. Mineral Springs are in some instances cold, in others warm, or even boiling. Thermal springs are more usually mineral waters than cold springs, but there does not appear to be any necessary relation between temperature and chemical composition. Mineral springs may be roughly classified for geological purposes according to the prevailing mineral substance contained in them, which may range in amount from 1 to 300 grammes per litre.[2]

Calcareous Springs contain calcium-carbonate in such quantity as to be deposited in the form of a white crust round objects over which the water flows. Calcium-carbonate, according to Fresenius, is dissolved by 10,600 of cold and by 8834 parts of warm water.[3] But in nature, the proportion of this carbonate present in springs depends mainly on the proportion of free carbonic acid, which retains the lime in solution. On the loss of carbonic acid by exposure and evaporation, the carbonate is thrown down as a white precipitate. This deposition is frequently brought about by the action of living plants. (Book III. Part II. Sect. iii. § 3.) Water saturated with carbonic acid will at the freezing-point dissolve 0·70 gramme and at 10° C. 0·88 gramme of calcium-carbonate per litre. Calcareous springs occur abundantly in limestone districts, and indeed may be looked for wherever the rocks are of a markedly calcareous character. In some regions, they have brought up such enormous quantities of lime as to form considerable hills (*postea*, p. 366).

Ferruginous or Chalybeate Springs contain a large proportion of ferrous sulphate (iron-vitriol, copperas) in the total mineral ingredients, and are known by their inky taste, and the yellow, brown, or red ochry deposit along their channel. They may be frequently observed in districts where beds or veins of pyritous ironstone occur, or where the rocks contain much iron-disulphide in combination, particularly in the waters of old mines. By the weathering of this sulphide (marcasite), so abundantly contained among stratified rocks, ferrous sulphate is produced and brought to the surface, but in presence of carbonates, particularly of the ubiquitous carbonate of lime, is decomposed, the acid being taken up by the alkaline earth or alkali, and the iron becoming a ferrous carbonate, which rapidly oxidizes and falls as the familiar yellow or brown crust of hydrous peroxide. The rapidity with which ferrous-carbonate is thus oxidized and precipitated was well shown by Fresenius in the case of the Langenschwalbach chalybeate spring. In its fresh state the water contains in 1000 parts 0·37696 of protoxide of iron. After standing twenty-four hours it was found to contain only 87·7 per cent of the original amount of iron; after sixty hours 62·9 per cent, and after eighty-four hours 53·2 per cent.[4]

Brine-Springs (Soolquellen) bring to the surface a solution in which sodium chloride greatly predominates. Springs of this kind appear where beds of solid rock-salt exist underneath, or where the rocks are impregnated with that mineral. Most of the brines worked as sources of salt are derived from artificial borings into saliferous rocks. Those of Cheshire in England, the Salzkammergut in Austria, Bex in Switzerland, &c., have long been well known. That of Clemenshall, Würtemberg, yields upwards of 26 per cent of salts, of which almost the whole is chloride of sodium. The other substances contained in solution in the water of brine-springs are chlorides of potassium, magnesium, and calcium; sulphates of calcium, and less frequently of sodium, potassium, magnesium, barium, strontium, or aluminium; silica; compounds of iodine and fluorine; with phosphates, arseniates, borates, nitrates, organic matter, carbon-dioxide, sulphuretted hydrogen, marsh-gas, and nitrogen.[1]

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[1] *Rivers Pollution Commission*, 6th Report, 1874, pp. 107-131. See also Reports of Brit. Assoc. Committee on underground circulation of water, beginning in 1876, and R. Warington's Report on experiments at the Rothamsted Laboratory, *Journ. Chem. Soc.* 1887.

[2] Paul, Watts' 'Dict. Chem.' v. p. 1016.

[3] Roth, 'Chem. Geol.' i. p. 48. "One litre of water, either cold or boiling, dissolves about 18 milligrammes." Roscoe and Schorlemmer, 'Chemistry,' ii. p. 208.

[4] *Journal für Prakt. Chem.* lxiv. 368, quoted by Roth, *op. cit.* i. p. 565. The river in the Vale of Avoca, Ireland, formerly contained so much ferrous sulphate, carried into it by mine-waters, that its bed and banks for several miles down to the sea were covered with an ochreous deposit.

Medicinal Springs, a vague term applied to mineral springs which have or are believed to have curative effects in different diseases. Medical men recognise various qualities, distinguished by the particular substance most conspicuous in each variety of water—*Alkaline Waters*, containing lime or soda and carbonic acid—Vichy, Saratoga; *Bitter Waters*, with sulphate of magnesia and soda—Sedlitz, Kissingen; *Salt* or *Muriated Waters*, with common salt as the leading mineral constituent—Wiesbaden, Cheltenham; *Earthy Waters*, lime, either a sulphate or carbonate being the most marked ingredient—Bath, Lucca; *Sulphurous Waters*, with sulphur as sulphuretted hydrogen and in sulphides—Aix-la-Chapelle, Harrogate. Some of these medicinal springs are thermal waters. Even where no longer warm, the water may have acquired its peculiar medicinal characters at a great depth, and therefore under the influence of increased temperature and pressure. Sulphur springs are sometimes warm, but also occur abundantly cold, where the water rises through rocks containing decomposing sulphides and organic matter. Sulphates are there first formed, which by the reducing effect of the organic matter are decomposed, with the resultant formation of sulphuretted hydrogen (p. 67). Sulphuretted hydrogen and sulphurous acid are sometimes oxidized into sulphuric acid, which remains free in the water.[2]

Hot Springs, Geysers.—The thermal waters of volcanic districts usually contain a marked percentage of dissolved mineral matter, notably silica, with sulphates, carbonates, chlorides, bromides, and other combinations. Perhaps the most detailed examination yet made of any such group of springs is the series of analyses performed by the Geological Survey of the United States on the waters of forty-three hot springs in the Yellowstone National Park. The temperatures of these waters ranged up to 93° C., and the total amount of dissolved mineral matter up to 2·8733 grammes in every kilogramme. The silica sometimes amounted to 0·6070 gramme, the sulphuric acid to 1·9330, the carbonic acid to 1·2490, the chlorine to 1·0442, the calcium to 0·3076, the magnesium to 0·0797, the potassium to 0·1603, the sodium to 0·4407, and there were minute quantities of numerous other constituents.[3]

Oil Springs.—Petroleum is sometimes brought up in drops floating in spring-water (St. Catherine's, near Edinburgh). In many countries it comes up by itself or mingled with inflammable gases. Reference has already been made (pp. 145, 235) to the abundance of this product in North America. In western Pennsylvania, some oil-wells have yielded as much as 2000 to 3000 barrels of oil per day. That the oil, which is specially confined to particular layers of rock in the Carboniferous and Devonian systems, arises from the alteration of organic substances embedded in the rocks of the crust, appears to be probable but no satisfactory explanation has been given of the nature and distribution of the organisms which yielded the oil.[4]

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[1] Roth, 'Chem. Geol.' i. p. 442. Bischof, 'Chem. Geol.' ii. Many subterranean waters, though not deserving the name of brines, contain considerable proportions of chlorides. On the alkaline chlorides of the Coal-measures see R. Malherbe, *Bull. Acad. Roy. Belgique*, 1875, p. 16; also R. Laloy, *Ann. Soc. Géol. Nord*, 1875, p. 195.

[2] Roth, *op. cit.* i. pp. 444, 452.

[3] F. A. Gooch and J. E. Whitfield, *Bull. U.S. Geol. Survey*, No. 47, 1888.

[4] See the authorities cited *ante*, p. 235.

Results of the Chemical Action of Underground Water.—Three remarkable results of the chemical operations of underground water are: 1st, The internal composition and minute structure of rocks are altered. 2nd, Enormous quantities of mineral matter are carried up to the surface, where they are partly deposited in visible form, and partly conveyed by brooks and rivers to the sea. 3rd, As a consequence of this transport, subterranean tunnels, passages, caverns, grottos, and other cavities of many varied shapes and dimensions are formed.

(1) *Alteration of Rocks.*—The processes of oxidation, deoxidation, solution, hydration, and the formation of carbonates, described (pp. 343, 344) as carried on above ground by rain, are likewise in progress on a great scale underneath. Since the permeability of subterranean rocks permits water to find its way through their pores as well as along their divisional planes, chemical changes, of a kind like those in ordinary weathering, take place in them, and at some depth may be intensified by internal terrestrial heat and pressure. This subterranean alteration of rocks may consist in the mere addition of substances introduced in chemical solution; in the simple solution and removal of some one or more constituents: or in a complex process of removal and replacement, wherein the original substance of a rock is molecule by molecule removed, while new ingredients are simultaneously or afterwards substituted. In tracing these alterations of rocks, the study of pseudomorphs becomes important, for we thereby learn what was the original composition of the mineral or rock. The mere existence of a pseudomorph points to the removal and substitution of mineral matter by permeating water.[1]

The extent to which such mineral replacement has been carried among rocks of the most varied structure and composition is probably best shown by the abundant petrified organic forms in formations of all geological ages. The minutest structures of plants and animals have been, particle by particle, removed and replaced by mineral matter introduced in solution, and this so imperceptibly, and yet thoroughly, that even minutiæ of organisation, requiring a high power of the microscope for their investigation, have been preserved without distortion or disarrangement. From this perfect condition of preservation, gradations may be traced until the organic structure is gradually lost amid the crystalline or amorphous infiltrated substance (Fig. 107). The most important petrifying media in nature are calcium-carbonate, silica, and iron-disulphide (marcasite more usually than pyrite). (See Book V.)

Another proof of the alteration which rocks have suffered from permeating water is supplied by the abundance of veins of calcite and quartz by which they are traversed, these minerals having been introduced in solution and often from the decomposition of the enclosing rock. As

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[1] It is not needful to take account here of such exceptional cases as the artificial conversion of aragonite into calcite by exposure to a high temperature. In such paramorphs the change is a molecular or crystalline rather than a chemical one, though how it takes place is still unknown. Pseudomorphs may be artificially formed. Crystals of atacamite ($Cu_4O_3Cl_2 + 4H_2O$) placed in a solution of bicarbonate of soda are completely changed into malachite in four years. Tschermak's *Min. Mitth.* 1877, p. 97.

Bischof pointed out, a drop of acid seldom fails to give effervescence on pieces of rock, composed of silicates, which have been taken even at some little depth from the surface, thus indicating the decomposition and deposit caused by permeating water. As already stated, one of the most remarkable results of the application of the microscope to geological inquiry is the extent to which it has revealed these all-pervading alterations, even in what might be supposed to be perfectly fresh rocks. Among the silicates, the most varied and complex interchanges have been effected. Besides the production of calcium-carbonate by the decomposition of such minerals as the lime-felspars, the series of hydrous green ferruginous silicates (delessite, saponite, chlorite, serpentine, &c.), so commonly met with in crystalline rocks, are usually witnesses of the influence of infiltrating water. The changes visible in olivine (p. 173) offer instructive lessons on the progress of transformation. One further example may be cited as supplied by the zeolites, so common in cavities and veins among many ancient volcanic and other crystalline rocks. These have commonly resulted from the decomposition of felspars or allied minerals. Their mode of formation is indicated by the observation already cited (p. 307), that Roman masonry at the baths of Plombières has in the course of centuries been so decomposed by the slow percolation of alkaline water at a temperature not exceeding 50° C. (122° Fahr.) under ordinary atmospheric pressure, that various zeolitic silicates have been developed in the brick.[1]

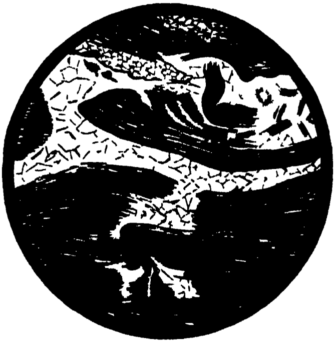

Fig. 107.—Fossil wood from tuff, Burntisland, showing parts perfectly preserved and parts destroyed by crystallization of calcite. Magnified 10 diameters.

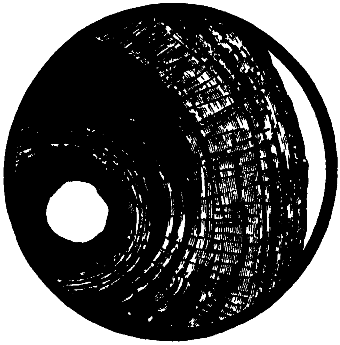

Fig. 108.—Section of a part of a Stalactite. Magnified 10 diameters.

(2) *Chemical Deposits.*—Of these by far the most abundant is calcium-carbonate. The way in which this substance is removed and re-deposited by permeating water can be instructively studied in the formation of the familiar *stalactites* and *stalagmites* beneath damp arches and in limestone caves (p. 150). As each drop gathers on the roof and begins to evaporate and lose carbonic acid, the excess of carbonate which it can no longer retain is deposited round its edges as a ring (Fig. 108). Drop succeeding

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[1] Daubrée, 'Géologie Expérimentale,' p. 179 *et seq.*

drop, the original ring grows into a long pendant tube, which, by subsequent deposit inside, becomes a solid stalk, and on reaching the floor may thicken into a massive pillar. At first the calcareous substance is soft and, when dry, pulverulent, but by prolonged saturation and the internal deposit of calcite it becomes by degrees crystalline. Each stalactite is found to possess an internal radiating fibrous structure, the fibres (prisms) passing across the concentric zones of growth. The stalactite remains saturated with calcareous water, and the divergent prisms are developed and continued as radii from the centre of the stalk. This process may be completed within a short period. At the North Bridge, Edinburgh, for example, which was erected in 1772, stalactites were obtained in 1874, some of which measure an inch and a half in diameter and possess the characteristic radiating structure.[1] It is doubtless by an analogous process that limestones, originally composed of the débris of calcareous organisms and interstratified among perfectly unaltered shales and sandstones, have acquired a crystalline structure (p. 122).[2]

Some calcareous springs deposit abundantly a precipitate of carbonate of lime upon mosses, twigs, leaves, stones, and other objects. The precipitate takes place when from any cause the water parts with carbonic acid. This may arise from mere evaporation, but is frequently due to the action of bog-mosses and water-plants, which, decomposing the carbonic acid, cause a crust of carbonate of lime to be deposited round their stems and branches (*postea*, p. 482). Hence calcareous springs are popularly called "petrifying," though they merely encrust organic bodies, and do not convert them into stone. Calc-sinter or travertine, as this precipitate is called, may be found in course of formation in most limestone districts, sometimes in masses large enough to form hills, and compact enough to furnish excellent building-stone. The travertine of Tuscany is deposited at the Baths of San Vignone at the rate of six inches a year, at San Filippo one foot in four months. At the latter locality it has been piled up to a depth of at least 250 feet, forming a hill a mile and a quarter long and a third of a mile broad.[3]

Chalybeate springs give rise to a deposit of hydrous peroxide of iron. This has already been referred to as a yellow and reddish-brown deposit along the channels of the water. Some acidulous springs, like those of the Laacher See, deposit large quantities of ochre. In undrained districts of temperate latitudes in Northern Europe and America, much iron is also deposited beneath soil which rests on a retentive subsoil. When the descending water is arrested on this subsoil, the iron, in solution as organic salts that oxidize into ferrous carbonate, is gradually converted into the insoluble hydrous ferric oxide, which is precipitated and forms a dark ferruginous layer, known to Scottish farmers as "moorband pan." So effectually does this layer interrupt the drainage that the soil remains permanently damp and unfertile. But when the "pan" is broken up and spread over the surface it quickly disintegrates, and improves the soil, which can then be properly drained (*postea*, p. 483).

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[1] The rate of deposit in the Ingleborough Cave is stated to be ·2946 inch per annum, or about 2½ feet in a century (Boyd Dawkins, Brit. Assoc. 1880, sects. p. 573). This is probably an exceptionally rapid growth.

[2] Sorby, Address to Geological Society, *Q. J. Geol. Soc.* 1879, p. 42 *et seq.* The finely fibrous structure seen in chalcedony under the microscope with polarized light passes in a similar way through the bands of growth of pebbles.

[3] Lyell, 'Principles,' i. p. 402. At Narni, the greater the velocity of flow, the greater the deposit of lime, very little being deposited in stagnant water. The amount thrown down increases with temperature and distance from source, exposure to the air being necessary for deposition. B. Fabri, *Proc. Inst. Civ. Engineers*, xli. (1876), p. 246. The student will find much detail regarding the abstraction and deposit of carbonate of lime by subterranean water in a paper by Senft, "Die Wanderungen und Wandelungen des kohlensauren Kalkes," *Z. Deutsch. Geol. Ges.* xiii. p. 263.

Siliceous springs form important masses of sinter round the point of outflow. The basins and funnels of geysers have already been described (p. 235). One of the sinter-beds in the Iceland geyser region is said to be two leagues long, a quarter of a league wide, and a hundred feet thick. Enormous beds of similar material have been formed in the Yellowstone geyser region. Such accumulations usually point to proximity to former volcanic centres, and are formed during one of the latest phases of volcanic action.

(3) *Formation of subterranean channels and caverns.*—Measurement of the yearly amount of mineral matter brought up to the surface by a spring, furnishes an approximate idea of the extent to which underground rocks undergo continual loss of substance. The warm springs of Bath, for example, with a mean temperature of 120° Fahr., are impregnated with sulphates of lime and soda, and chlorides of sodium and magnesium. Sir A. C. Ramsay estimated their annual discharge of mineral matter to be equal to a square column 9 feet in diameter and 140 feet in height. Again, the St. Lawrence spring at Louèche (Leuk) discharges every year 1620 cubic metres (2127 cubic yards) of dissolved sulphate of lime, equivalent to the lowering of a bed of gypsum one square kilometre (0·3861 square mile) in extent, more than 16 decimetres (upwards of five feet) in a century.[1]

By prolonged abstraction of this nature, subterranean tunnels, channels, and caverns have been formed. In regions abounding in rock-salt deposits, the result of the solution and removal of these by underground water is visible in local sinkings of the ground and the consequent formation of pools and lakes. The landslips and meres of Cheshire are illustrations of this process. In that county, owing to the pumping out of the brine in the manufacture of salt, tracts of ground sometimes more than 100 acres in extent have sunk down and become the sites of lakes of varying depth, some being 45 feet deep.[2] In calcareous districts, still more striking effects are observable. The ground may there be found drilled with vertical cavities (*swallow-holes, sinks, dolinas*), by the solution of the rock along lines of joint or of faults that serve as channels for descending rain-water. The line of outcrop of a limestone-band, among non-calcareous strata, may often be traced, even under a covering of superficial deposits, by its row of swallow-holes. Surface-drainage, thus intercepted, passes at once underground, where, in course of time, an elaborate system of spacious tunnels and chambers may be dissolved out of the solid rock (Fig. 111). Such has been the origin of the Peak caverns of Derbyshire, the intricate grottos of Antiparos and Adelsberg, and the vast labyrinths of the Mammoth Cave of Kentucky.[1] In the course of time, the underground rivers open out new courses, and leave their old ones dry, as the Poik has done at Adelsberg. By the falling in of the roofs of caverns, a communication is established with the surface, and land-shells and land-animals fall into the holes, or the caverns are used as dens by beasts of prey, so that the remains of terrestrial animals are preserved under the stalagmite. Not unfrequently caverns, once open and freely used as haunts of carnivora, have had their entrances closed by the fall of débris, as at *d* in Fig. 110, where also the partial filling-up of a cavern (*a a*) from the same cause is seen. Where the collapse of a cavern roof takes place below a water-course, the stream is engulfed. In this way, brooks and rivers suddenly disappear from the surface, and after a long subterranean course, issue again in a totally different surface-area of river-drainage from that in which they took their rise, and sometimes with volume enough to be

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[1] E. Reclus, 'La Terre,' i. p. 340.

[2] T. Ward, "History and Cause of the subsidences at Northwich, &c." 1887, *Geol. Mag.* 1887, p. 517.

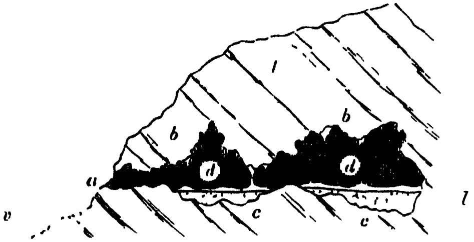

Fig 109.—Section of a Limestone Cavern (*B.*)

l l, A limestone hill, perforated by a cavern (*b b*) which communicates with the valley (*v*) by an opening (*a*). The bottom of the cavern is covered with ossiferous loam, above which lies a layer of stalagmite (*d d*), while stalactites hang from the roof, and by joining the floor separate the cavern into two chambers.

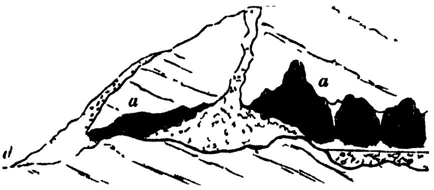

Fig 110.—Section of a Limestone Cavern with fallen-in roof and concealed entrance (*B.*)

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[1] For accounts of the remarkable honeycombed region of Carniola, &c., see Mojsisovics, 'Geologie von Bosnien-Hercegovina,' pp. 44-60; *Zeitsch. Deutsch. Alpenvereins*, 1880. E Tietze, *Jahrb. Geol. Reichsanst.* xxx. (1880), p. 729, and papers cited by him. Dr. J. H Kloos and Dr. Max Muller, description and photographs of the Hermann's Cave of Rubeland in Brunswick (Weimar, 1889).

navigable almost up to their outflow. In such circumstances, lakes, either temporary, like the Lake Zirknitz in Carniola, or perennial, may be formed over the sites of the broken-in caverns; and valleys may thus be deepened, or gorges may be formed.[1] Mud, sand, and gravel, with the remains of plants and animals, are swept below ground, and sometimes accumulate in deposits of loam and breccia, such as are so often found in ossiferous caverns (Figs. 109, 110).

As from time to time the roofs of underground chambers, weakened by the constant abstraction of mineral matter, collapse, or large portions are detached from them and fall on the floors below, sudden shocks are generated which are felt above ground as earthquakes. In subsiding to fill up hollows from which the rock has been removed in solution, the overlying strata may be greatly contorted and fractured, those underneath remaining undisturbed.

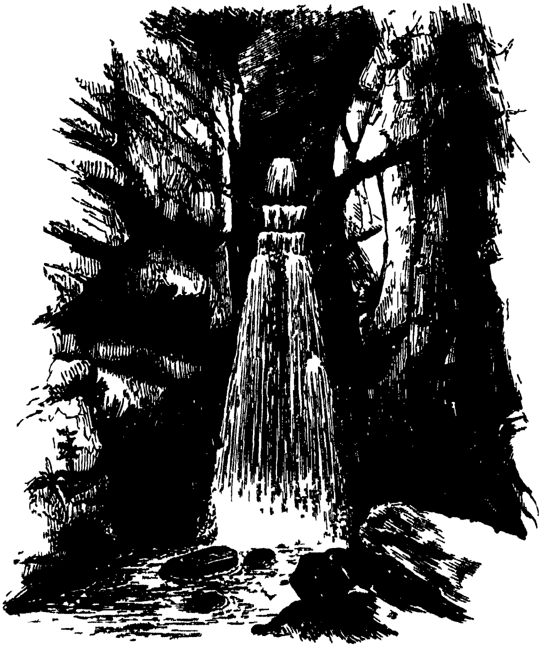

Fig 111 —Section of the channel of an underground stream

2. **Mechanical Action.**—In its passage along fissures and channels, underground water not merely dissolves and removes materials in solution, it likewise loosens finer particles and carries them along in mechanical suspension. This removal of material sometimes produces remarkable surface-changes along the sides of steep slopes or cliffs A

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[1] See interesting accounts by M. Martel of the subterranean channels of the Causses or Jurassic limestone plateaux of Gard and Lozère in the South of France, and of the formation of cañons there. *Compt. rend.* 1888. *Bull. Soc. Géol. France*, xvii (1889), p. 610.

thin porous layer, such as loose sand or ill-compacted sandstone, lying between more impervious rocks, such as masses of clay or limestone, and sloping down from higher ground, so as to come out to the surface near the base of a line of abrupt cliff, serves as a channel for underground water which issues in springs or in a more general oozing at the foot of the declivity. Under these circumstances the support of the overlying mass of rock is apt to be loosened; for the water not only removes piecemeal the sandy layer on which that overlying mass rests, but, as it were, lubricates the rock underneath. Consequently, at intervals, portions of the upper rock break off and slide down into the valley or plain below. Such dislocations are known as *landslips*.[1] The movement may be gradual, as in the case of the Bec Rouge in the Tarentaise, where the side of the mountain is slowly overwhelming the village of Miroir,[2] or it may be sudden and disastrous.

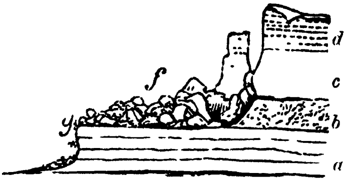

Fig. 112.—Section of Landslip forming undercliff, Pinhay, Lyme-Regis (*B.*)

Along sea-coasts and river valleys, at the base of cliffs subject to continual or frequent removal of material by running water, the phenomena of landslips are best seen. The coast-line of the British Islands abounds with instructive examples. On the shores of Dorsetshire, for instance (Fig. 112), impervious Liassic clays (*a*) are overlain by porous greensand (*b*), above which lies chalk (*c*) capped with gravel (*d*). In consequence of the percolation of water through the sandy zone (*b*), the support of the overlying mass is destroyed, and hence, from time to time, segments are launched down towards the sea. In this way, a confused medley of mounds and hollows (*f*) forms a characteristic strip of ground termed the "Undercliff" on this and other parts of the English coasts. This recession of the upper or inland cliff through the operation of springs is here more rapid than that of the lower cliff (*g*) washed by the sea.[3] In the year 1839, after a season of wet weather, a mass of chalk on the same coast slipped over a bed of clay into the sea, leaving a rent three-quarters of a mile long, 150 feet deep, and 240 feet wide. The shifted mass, bearing with it houses, roads, and fields, was cracked, broken, and tilted in various directions, and was thus prepared for further attack and removal by the waves.[4] In February 1891 a mass of chalk-cliff calculated to contain some 10,000 tons of material gave way on the cliffs to the east of Brighton, and fell to the beach, breaking away part of the main road above. In March 1893 by an extensive slipping of the Lower Greensand towards the beach a large part of the town of Sandgate on the coast of Kent was destroyed. The antiquity of many landslips is shown by the ancient buildings occasionally to be seen upon the fallen masses. The undercliff of the Isle of Wight, the cliffs west of Brandon Head, county Kerry, the basalt escarpments of Antrim, and the edges of the great volcanic plateaux of Mull, Skye, and Raasay, furnish illustrations of such old and prehistoric landslips.

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[1] Baltzer, in his work "Ueber Bergsturze in den Alpen" (Zurich, 1875), classifies Swiss landslips into four categories, viz., 1st, Rock-falls (Felssturze); 2nd, Earth-slips (Erdschliffe); 3rd, Mud-streams (Schlammstrome), where soft strata saturated with water are crushed by the weight of overlying rock and move down in mass, like lava; 4th, Mixed falls (gemischte Sturze), where, as in most instances, rock, earth, and mud are launched down the declivities. More recently he has offered another classification of landslips, according to the dimensions of the mass moved and the solid or muddy condition of the material, *Neues Jahrb.* 1880 (ii.), p. 198. See A. Rothpletz, *Zeitsch. Deutsch. Geol. Ges.* 1881, p. 540; also *op. cit.* 1882, pp. 430, 435. E. Buss and A. Heim, 'Der Bergsturz von Elms,' Zurich, 1881.

[2] L. Borrell, *Bull. Soc. Géol. France*, sér. 3, vi. (1877), p. 47.

[3] De la Beche, 'Geol. Observer,' p. 22.

[4] Conybeare and Buckland's 'Axmouth Landslip,' London, 1840. Lyell, 'Principles,' i. p. 536.

On a more imposing scale, and interesting from its melancholy circumstances being so well known, was the celebrated fall of the Rossberg, a mountain (*a*, Fig. 113) situated behind the Rigi in Switzerland, rising to a height of more than 5000 feet above the sea. After the rainy summer of 1806, a large part of one side of the mountain, consisting of steeply sloping beds of hard red sandstone and conglomerate (*b*), resting upon soft sandy layers (*c c*), gave way. The lubrication of the lower surface by the water having loosened the cohesion of the overlying mass, thousands of tons of solid rock, set loose by mere gravitation, suddenly swept across the valley of Goldau (*d*), burying about a square German mile of fertile land, four villages containing 330 cottages and outhouses, with 457 inhabitants.[1] In 1855 a mass of débris, 3500 feet long, 1000 feet wide, and 600 feet high, slid into the valley of the Tiber, which, dammed back by the obstruction, overflowed the village of San Stefano to a depth of 50 feet, until drained off by a tunnel.

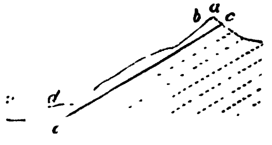

Fig. 113.—Section illustrating the Fall of the Rossberg.

§ 3. Brooks and Rivers.

These will be considered under four aspects :—(1) sources of supply, (2) discharge, (3) flow, and (4) geological action.[2]

1. **Sources of Supply.**—Rivers, as the natural drains of a land-surface, carry out to sea the surplus water after evaporation, together with a vast amount of material worn off the land. Their liquid contents are derived partly from rain (including mist and dew) and melted snow, partly from springs. In a vast river-system, like that of the Mississippi, where the area of drainage is so extensive as to embrace different climates and varieties of rainfall, the amount of discharge, being in a great measure independent of local influences of weather, remains tolerably uniform, or is subject to regular periodically-recurrent variations. In smaller rivers, such as those of Britain, whose basins lie in a region having the same general features of climate, the quantity of water is regulated by the local rainfall. A wet season swells the streams, a dry one diminishes them. Hence, in estimating and comparing the geological work done by different rivers, we must take into account whether or not the sources of supply are liable to occasional great augmentation or diminution. In some rivers, there is a more or less regularly recurring season of flood followed by one of drought. The Nile, fed by the spring rains of Abyssinia, floods the plains of Egypt

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[1] Zay, 'Goldau und seine Gegend.' Baltzer *Neues Jahrb.* 1875, p. 15. Upwards of 150 destructive landslips have been chronicled in Switzerland. Riedl, *Neues Jahrb.* 1877, p. 916.

[2] An excellent monograph on a river is C. Lenthéric's 'Le Rhône, histoire d'un fleuve,' 2 vols. Paris, 1892.

every summer, rising in Upper Egypt from 30 to 35 feet, at Cairo 23 to 24 feet, and in the seaward part of the delta about 4 feet. The Ganges and its adjuncts begin to rise every April, and continue doing so until the plains are converted into a vast lake 32 feet deep. In other rivers, sudden and heavy rains, occurring at irregular intervals, swell the usual volume of water and give rise to floods, freshets, or "spates." This is markedly the case with the rivers of Western Europe. Thus the Rhone sometimes rises 11½ feet at Lyons and 23 feet at Avignon; the Saône from 20 to 24½ feet. In the middle of March 1876, the Seine rose 20 feet at Paris, the Oise 17 feet near Compiègne, the Marne 14 feet at Damery. The Ardèche at Gournier exceeded a rise of 69 feet during the inundations of 1827.[1] The causes of floods, not only as regards meteorological conditions, but in respect to the geological structure of the ground, merit the careful attention of the geological student. He may occasionally observe that, other things being equal, the volume of a flood is less in proportion to the permeability of a hydrographic basin, and the consequent ease with which rain can sink beneath the surface.

Were rivers entirely dependent upon direct supplies of rain, they would only flow in rainy seasons and disappear in drought. This does not happen, however, because they derive much of their water not directly from rain, but indirectly through the intermediate agency of springs. Hence they continue to flow even in very dry weather, because, though the superficial supplies have been exhausted, the underground sources still continue available. In a long drought, the latter begin at length to fail, the surface springs ceasing first, and gradually drying up in their order of depth, until at last only deep-seated springs furnish a perhaps daily diminishing quantity of water. Though it is a matter of great economic as well as scientific interest to know how long any river would continue to yield a certain amount of water during a prolonged drought, no rule seems possible for a generally applicable calculation, every area having its own peculiarities of underground drainage, and varying greatly from year to year in the amount of rain which is absorbed. The river Wandle, for instance, drains an area of 51 square miles of the chalk downs in the south-east of England. For eighteen months, from May 1858 to October 1859, as tested by gauging, there was very little absorption of rainfall over the drainage basin, and yet the minimum recorded flow of the Wandle was 10,000,000 gallons a day, which represents not more than ·4090 inch of rain absorbed on the 51 square miles of chalk. The rock is so saturated that it can continue to supply a large yield of water for eighteen months after it has ceased to receive supplies from the surface, or at least has received only very much diminished supplies.[2]

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[1] For a graphic account of rivers swollen by heavy rainfall, see Sir T. D. Lauder's 'Morayshire Floods.' On torrents consult Surell and Cézanne, 'Études sur les Torrents des Hautes Alpes.'

[2] Lucas, 'Horizontal Wells,' London, 1874, pp. 40, 41. See also Braithwaite, *Min. Proc. Inst. Civ. Engin.* xx. It is much to be desired that such observations as those of Sir J. B. Lawes, Dr. Gilbert, and Sir John Evans on the percolation of rain through soils and chalk

2. **Discharge.**—What proportion of the total rainfall is discharged by rivers is another question of great geological and industrial interest. From the very moment that water takes visible form, as mist, cloud, dew, rain, snow, or hail, it is subject to evaporation. When it reaches the ground, or flows off into brooks, rivers, lakes, or the sea, it undergoes continual diminution from the same cause. Hence in regions where rivers receive no tributaries, they grow smaller in volume as they move onward, till in dry hot climates they even disappear. Apart from temperature, the amount of evaporation is largely regulated by the nature of the surface from which it takes place, one soil or rock differing from another, and all of them probably from a surface of water. Full and detailed observations are still wanting for determining the relation of evaporation to rainfall and river discharge.[1] During severe storms of rain, the water discharged over the land finds its way, to a very large extent, at once into brooks and rivers, by which it reaches the sea. Mr. David Stevenson remarks that, according to different observations, the amount carried off in floods varies from 1 to 100 cubic feet per minute per acre.[2] In estimating and comparing, therefore, the ratios between rainfall and river discharge in different regions, regard must be had to the nature of the rainfall, whether it is crowded into a rainy season or diffused over the year. Thus, though floods cannot be deemed exceptional phenomena, forming as they do a part of the regular system of water-circulation over the land, they do not represent the ordinary proportions between rainfall and river discharge in such a climate as that of Britain, where the rainfall is spread more or less equally throughout the year. According to Beardmore's table,[3] the Thames at Staines has a mean annual discharge of 32·40 cubic inches per minute per square mile, equal to a depth of 7·31 inches of rainfall run off, or less than a third of the total rainfall. The most carefully collected data at present available are probably those given by Humphreys and Abbot for the basin of the Mississippi and its tributaries, as shown in the subjoined table[4]:—

(*Min. Proc. Inst. Civ. Engin.* xlv. p. 208; see also Greaves, *op. cit.* p. 19) should be tried in many different areas.

[1] In the present state of our information it seems almost useless to state any of the results already obtained, so widely discrepant and irreconcilable are they. In some cases, the evaporation is given as usually three times the rainfall: and that evaporation always exceeded rainfall was for many years the belief among the French hydraulic engineers. (See *Annales des Ponts-et-Chaussées*, 1850, p. 383.) Observations on a larger scale, and with greater precautions against the undue heating of the evaporator, have since shown, as might have been anticipated, that as a rule, save in exceptionally dry years, evaporation is lower than rainfall. As the average of ten years from 1860 to 1869, Mr. Greaves found that at Lea Bridge the evaporation from a surface of water was 20·946 inches, while the rainfall was 25·534 (Symons's *British Rainfall* for 1869, p. 162). But we need an accumulation of observations, taken in many different situations and exposures, in different rocks and soils, and at various heights above the sea. (For a notice of a method of trying the evaporation from soil, see *British Rainfall*, 1872, p. 206.)

[2] 'Reclamation and Protection of Agricultural Land,' Edin. 1874, p. 15.

[3] 'Hydrology, p. 201. Comp. Report of Royal Commission on Water Supply, 1869, p. liii.

[4] 'Physics and Hydraulics of the Mississippi River,' Washington, 1861, p. 136.

	Ratio of Discharge to Rainfall.
Ohio River	0·24
Missouri River	0·15
Upper Mississippi River	0·24
Small Tributaries	0·90
Arkansas and White River	0·15
Red River	0·20
Yazoo River	0·90
St. Francis River	0·90
Entire Mississippi, exclusive of Red River	0·25

In the Mississippi basin, one-fourth of the rainfall is thus discharged into the sea. The Elbe, from the beginning of July 1871 to the end of June 1872, was estimated to carry off at most a quarter of the rainfall from Bohemia.[1] The Seine at Paris appears to carry off about a third of the rainfall. In Great Britain from a fourth to a third part of the rainfall is perhaps carried out to sea by streams.[2]

In comparing also the discharges of different rivers, regard should be paid to the influence of geological structure, and particularly of the permeability or impermeability of the rocks, as regulating the supply of water to rivers. Thus the Thames, from a catchment basin of 3670 square miles and with a rainfall of 27 inches, has a mean annual discharge at Kingston of 1250 millions of gallons a day, and rather more than 688 millions of gallons in summer. The Severn, on the other hand, which gathers its supplies mainly from the hard, impervious slate hills of Wales, has a drainage area above Gloucester of 3890 square miles, with an average rainfall of probably not less than 40 inches. Yet its daily summer discharge does not amount to 298 millions of gallons, and its minimum sinks as low as 100 millions of gallons, while that of the Thames in the driest season never falls below 350 millions. In the one case, the water is stored up within the rocks and is dispensed gradually; in the other, it in great measure runs off at once.[3] It is likewise deserving of note that the operations of man, particularly in draining land and deforesting, may materially alter the mean level of a river and increase the volume of floods. The mean level of the Elbe at Dresden is said to have been perceptibly diminished by human interference, while in the Rhine the low-water level has been lowered, and the floods have been augmented.[4]

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[1] *Verhandl. Geol. Reichsanstalt*, Vienna, 1876, p. 173.

[2] In mountainous tracts having a large rainfall and a short descent to the sea, the proportion of water returned to the sea must be very much greater than this. Mr. Bateman's observations for seven years in the Loch Katrine district gave a mean annual rainfall of 87½ inches at the head of the lake, with an outflow equivalent to a depth of 81·70 inches of rain removed from the drainage basin of 71½ square miles. See a paper by Graeve on the quantity of water in German rivers, and on the relation between rainfall and discharge, *Der Civil-Ingenieur*, 1879, p. 591; *Nature*, xxiii. p. 94. J. Murray, *Scott. Geog. Mag.* 1887.

[3] Prestwich, *Q. J. Geol. Soc.* xxviii. p. lxv. Compare the conditions of the catchment basin of the Seine as given by A. Delaire, *Ann. Conserv. Arts et Métiers*, No. 138, p. 335.

[4] Report of (Austrian) Committee on Diminution of Water in Springs and Rivers, *Proc. Inst. Civ. Engineers*, xlii. (1875), p. 271.

3. **Flow.**—While, in obedience to the law of gravitation, a river always flows from higher to lower levels, great variations in the rate and character of its motion are caused by inequalities in the angle of slope of its channel. A vertical or steeply inclined face of rock originates a waterfall; a rocky declivity in the channel gives rise to rapids; a flat plain allows the stream to linger with a scarcely visible current; while a lake renders the flow nearly or altogether imperceptible. Thus the rate of flow is regulated in the main by the angle of inclination and form of the channel, but partly also by the volume of water, an increase of volume in a narrow channel increasing the rate of motion even without an increase of slope.[1]

The course of a great river may be divided into three parts:—1. *The Mountain Track,*—where, amidst clouds or snows, it takes its rise as a mere brook, and, fed by innumerable similar torrents, dashes rapidly down the steep sides of the mountains, leaping from crag to crag in endless cascades, and growing every moment in volume, until it enters lower ground. 2. *The Valley Track,*—where, now flowing through lower hills or undulations, the stream is found at one time in a wide fertile valley, then in a dark gorge, now falling headlong into a cataract, now expanding into a broad lake. This is the part of its career where it assumes the most varied aspects, and receives the largest tributaries. 3. *The Plain Track,*—where, having quitted the undulating region, the river finally emerges upon broad plains, probably wholly or in great part composed of alluvial formations deposited by its own waters. Here winding sluggishly in wide curves, it may eventually bifurcate, as it approaches the sea and spreads through its delta, enclosing tracts of flat meadow or marsh, and finally, amid banks of mud and sand, passing out into the great ocean. In Europe, the Rhine, Rhone, and Danube; in Asia, the Ganges and Indus; in America, the Mississippi and Amazon; in Africa, the Nile and Niger—illustrate this typical course of a great river.

If we draw a longitudinal section of the course of any such river or of any of its tributaries from its source, or from the highest peaks around that source, to its mouth, we find that the line at first curves steeply from the mountain crests down into the valleys, but grows less and less inclined through the middle portion, until it finally can hardly be distinguished from a horizontal line. This feature, however, is not confined to stream courses but belongs to the architecture of the continents.

It is evident that a river must flow, on the whole, fastest in the first portion of its course, and slowest in the last. The common method of comparing the fall or slope of rivers is to divide the difference of height between their source and the sea-level by their length, so as to give the declivity per mile. This mode, however, often fails to bring out the real resemblances and differences of rivers, even in regard to their angle of slope. For example, two streams rising at a height of 1000 feet, and flowing 100 miles to the sea, would each have an average slope of 10 feet per mile; yet they might be wholly unlike each other, one making its descent almost entirely in the first or mountain part of its course, and lazily winding for most of its way through a vast low plain; the other toiling through the mountains, then keeping among hills and table-lands, so as to form on the whole a tolerably equable and rapid flow. The great rivers of the globe have probably a less average slope than 2 feet per mile, or 1 in 2640. The Missouri, which has a descent of 28 inches per mile, is a tumultuous rapid current even down as far as Kansas City. The average slope of the channel of the Thames is 21 inches per mile; of the Shannon about 11 inches per mile, but between Killaloe and Limerick about 6½ feet per mile; of the Nile, below Cairo, 3·25 to 5·5 inches per mile; of the Doubs and Rhone, from Besançon to the Mediterranean, 24·18 inches per mile; of the Volga from its source to the sea, a little more than 3 inches per mile. Higher angles of descent are those of torrents, as the Arve, with a slope of 1 in 616 at Chamounix, and the Durance, whose angle varies from 1 in 467 to 1 in 208. The Colorado river rushes through its cañons with an average declivity of 7·72 feet per mile, or 1 in 683. The slope of a navigable river ought hardly to exceed 10 inches per mile, or 1 in 6336.[1]

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[1] See A. Tylor on the Laws of River-action, *Geol. Mag.* 1875, p. 443.

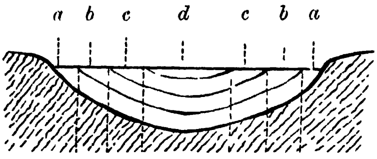

Fig. 114.—Cross-section of a River.

But not only does the rate of flow of a river vary at different parts of its course, it is not the same in every part of the cross-section of the river taken at any given point. A river channel (Fig. 114) supports a succession of layers of water (*a*, *b*, *c*, *d*), moving with different velocities, the greatest movement being at the centre (*d*), and the least in the layer which lies directly on the channel. At the same vertical depth, therefore, the velocity is greater in proportion as the point approaches the centre of the stream. The water next the sides and bottom (*a a*), being retarded by friction against the channel, moves less rapidly than the layers (*b b*, *c c*) towards the centre (*d*). The central piers of a bridge have consequently a greater velocity of river-current to bear than those at the banks. The motion of the surface-water, however, is retarded, on the other hand, by upward currents, generated chiefly by irregularities of the bottom.[2] It follows that whatever tends to diminish the friction of the moving current will increase its rate of flow. The same body of water, other conditions being equal, will move faster through a narrow gorge with steep smooth walls than over a broad rough rocky bed. For the same reason, when two streams join, their united current, having in many cases a channel not much larger than that of one of the single streams, flows faster, because the water encounters now the friction of only one channel. The average rate of flow is much less than might be supposed, even in what are termed swift rivers. A moderate current is about 1¼ mile in the hour; even that of a torrent does not exceed 18 or 20 miles in the hour. Mr. D. Stevenson states that the velocity of such rivers as the Thames, the Tay, or the Clyde may be found to vary from about one mile per hour as a minimum to about three miles per hour as a maximum velocity.[1]

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[1] D. Stevenson, 'Canal and River-Engineering,' p. 224.

[2] J. Thomson, *Proc. Roy. Soc.* xxviii. (1878), p. 114. Comp. Collignon, 'Cours d' Hydraulique,' p. 301.

It may be remarked, in concluding this part of the subject, that elevations and depressions of land must have a powerful influence upon the slope of rivers. The upraising of the axis of a country, by increasing the slope, augments the rate of flow, which, on the contrary, is diminished by a depression of the axis or by an elevation of the maritime regions.

4. **Geological Action.**—Like all other forms of moving water, streams have both a *chemical* and *mechanical* action. The latter receives most attention, as it undoubtedly is the more important; but the former ought not to be omitted in any survey of the general waste of the earth's surface.

i. Chemical.—The water of rivers must possess the powers of a chemical solvent, like rain and springs, though its actual work in this respect can be less easily measured, seeing that river-water is directly derived from rain and springs, and necessarily contains in solution mineral substances supplied to it by them. Nevertheless, that streams dissolve chemically the rocks of their channels can be strikingly seen in limestone districts, where the lower portions of the ravines may be found enlarged into wide cavities or pierced with tunnels and arches, presenting in their smooth surfaces a great contrast to the angular jointed faces of the same rock where exposed to the influence only of the weather.[2]

Daubrée endeavoured to illustrate the chemical action of rivers upon their transported pebbles by exposing angular fragments of felspar to prolonged friction in revolving cylinders of sandstone containing distilled water. He found that they underwent considerable decomposition, as was shown by the presence of silicate of potash, rendering the water alkaline. Three kilogrammes of felspar fragments made to revolve in an iron cylinder for a period of 192 hours, which was equal to a journey of 460 kilometres (287 miles), yielded 2·720 kilogrammes of mud, while the five litres of water in which they were kept moving contained 12·60 grammes of potash, or 2·52 grammes per litre.[3]

The mineral matter held in solution in river-water is, doubtless, partly derived from the mechanical trituration of rocks and detritus; for Daubrée's experiments show that minerals which resist the action of acid may be slowly decomposed by mere mechanical trituration, such as takes place along the bed of a river. But in sluggish streams the main supply of mineral solution is doubtless furnished by springs.

The proportion of mineral matter in river-water varies with the season, even for the same stream. It reaches its maximum when the water is mainly derived from springs, as in very dry weather and during frost; it attains its minimum in rainy seasons and after rain.[4] Its amount and composition depend upon the nature of the rocks forming the drainage-basin. Where these are on the whole impervious, the water runs off with comparatively slight abstraction of mineral ingredients; but where they are permeable, the water, in sinking through them and rising again in springs, dissolves their substance and carries it into the rivers.

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[1] 'Reclamation of Land,' p. 18.

[2] For an illustration of this action by the Rhone in the marine molasse, see F. Cuvier, *Bull. Soc. Géol. France*, 3me sér. viii. p. 164.

[3] 'Géologie Expérimentale, p. 271; Fayol, *Bull. Soc. Géol. France*, 3me sér. xvi. p. 996, *postea*, p. 385.

[4] Roth, 'Chem. Geol.' i. p. 454.

The composition of the river-waters of Western Europe is well shown by numerous analyses. The substances held in solution include variable proportions of the atmospheric gases, carbonates of lime, magnesia, soda, iron, and ammonia; silica; peroxides of iron and manganese; alumina; sulphates of lime, magnesia, potash, and soda; chlorides of sodium, potassium, calcium, and magnesium; silicate of potash; nitrates; phosphoric acid: and organic matter. The minimum proportion of mineral matter among the analyses collected by Bischof was 2·61 in 100,000 parts of water in the Moll, near Heiligenblut—a mountain stream 3800 feet above the sea, flowing from the Pasterzen glacier over crystalline schists. On the other hand, as much as 54·5 parts in the 100,000 were obtained in the waters of the Beuvronne, a tributary of the Loire above Tours. The average of the whole of these analyses is about 21 parts of mineral matter in 100,000 of water, whereof carbonate of lime usually forms the half, its mean quantity being 11·34.[1] Bischof calculated that, assuming the mean quantity of carbonate of lime in the Rhine to be 9·46 in 100,000 of water, which is the proportion ascertained at Bonn, enough of this substance is carried into the sea by this river for the annual formation of three hundred and thirty-two thousand millions of oyster-shells of the usual size. The mineral next in abundance is sulphate of lime, which in some rivers constitutes nearly half of the dissolved mineral matter. Less in amount are sodium chloride,[2] magnesium carbonate and sulphate, and silica. Of the last-named, a percentage amounting to 4·88 parts in 100,000 of water has been found in the Rhine, near Strasburg.[3] The largest amount of alumina was 0·71 in the Loire, near Orleans. The proportion of mineral matter in the Thames, near London, amounts to about 33 parts in 100,000 of water.[4]

It requires some reflection properly to appreciate the amount of solid mineral matter which is every year carried in solution from the rocks of the land and diffused by rivers into the sea. Accurate measurements of the amount of material so transported are still much required. The Thames carries past Kingston 19 grains of mineral salts in every gallon, or 1502 tons every twenty-four hours, or 548,230 tons every year. Of this quantity about two-thirds consist of carbonate of lime, the rest being chiefly sulphate of lime, with minor proportions of the other ordinary salts of river-water. Mr. Prestwich estimates that the quantity of carbonate of lime removed from the limestone areas of the Thames basin amounts to 140 tons annually from every square mile. This quantity, assuming a ton of chalk to measure 15 cubic feet, is equal to a loss of $\frac{9}{100}$ of an inch from each square mile in a century, or one foot in 13,200 years.[5] According to monthly observations and estimates made in the year 1866 at Lobositz, near the exit of the Elbe from its Bohemian basin, this river may be regarded as carrying every year out of Bohemia from an area of 880 German square miles, or, in round numbers, 20,000 English square miles, 6,000,000,000 cubic metres of water, containing 622,680,000 kilogrammes of dissolved and 547,140,000 of suspended matter, or a total of 1169 millions of kilogrammes. Of this total, 978 millions of kilogrammes consist of fixed and 192 millions of volatile (chiefly organic) matter. The proportions of some of the ingredients most important in agriculture were estimated as follows: lime, 140,380,000 kilogrammes; magnesia, 28,130,000; potash, 54,520,000; soda, 39,600,000; chloride of sodium, 25,320,000; sulphuric acid, 45,690,000; phosphoric acid, 1,500,000.[1]

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[1] Bischof, 'Chem. Geol.' i. chap. v. Of the analyses, chiefly of European rivers, published by Roth, the mean of thirty-eight gives a proportion of 19·983 in 100,000 parts of water. *Op. cit.* p. 456. Compare I. C. Russell, *Bull. U.S. Geol. Surv.* 1889.

[2] On the variations of the chlorine in the Nile and Thames, see J. A. Wanklyn, *Chem. News*, xxxii. (1875), pp. 207, 219.

[3] Of the total solid matter dissolved in the water of the River Uruguay as much as about 46 per cent consists of soluble silica, chiefly as hydrated silicic acid. Hence the "petrifying" property of the water. J. Kyle, *Chem. News*, xxxviii. (1878), p. 28.

[4] Bischof, *op. et loc. cit.*; Roth, *op. cit.* i. p. 454. For composition of British river-water, see 'Rivers Pollution Commission Report.'

[5] Prestwich, *Q. J. Geol. Soc.* xxviii. p. lxvii.

Mr. T. Mellard Reade has estimated that a total of 8,370,630 tons of solids in solution is every year removed by running water from the rocks of England and Wales, which is equivalent to a general lowering of the surface of the country, from that cause alone, at a rate of ·0077 of a foot in a century, or one foot in 12,978 years. The same writer computes the annual discharge of solids in solution by the Rhine to be equal to 92·3 tons per square mile, that of the Rhone at Avignon 232 tons, that of the Danube 72·7 tons, and that of the Mississippi 120 tons. He supposes that on an average over the whole world there may be every year dissolved by rain about 100 tons of rocky matter per English square mile of surface.[2]

If the average proportion of mineral matter in solution in river-water be taken as only 2 parts in every 10,000 by weight, then it is obvious that in every 5000 years the rivers of the globe must carry to the sea their own weight of dissolved rock.

ii. Mechanical.—The mechanical work of rivers is threefold:—(1) to transport mud, sand, gravel, or blocks of stone from higher to lower levels; (2) to use these loose materials in eroding their channels; and (3) to deposit these materials where possible, and thus to make new geological formations.[3]

1. *Transporting Power.*[4]—One of the distinctions of river-water, as compared with that of springs, is that as a rule, it is less transparent, in other words, contains more or less mineral matter in suspension.[5] A sudden heavy shower, or a season of wet weather, suffices to render turbid a river which was previously clear. The mud is washed into the main streams by rain and brooks, but is partly produced by the abrasion of the water-channels through the operations of the streams themselves. The channels of the mountain-tributaries of a river are choked with large fragments of rock disengaged from cliffs and crags on either side. Traced downwards, the blocks become gradually smaller and more rounded. They are ground against each other and upon the rocky sides and bottom of the channel, becoming more and more reduced as they descend, and at the same time abrading the rocks over or against which they are driven. Of the detritus thus produced, the finer portions are carried in suspension,

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[1] Breitenlohner, *Verhand. Geol. Reichsanst.* Vienna, 1876, p. 172. Taking the 978,000,000 kilogrammes to be mineral matter in solution and suspension, this is equal to an annual loss of about 48 tons per English square mile. But it includes all the materials discharged by the drainage of an abundant population.

[2] Addresses, *Liverpool Geol. Soc.* 1876 and 1884.

[3] On the behaviour of rivers, consult Dausse, 'Études relatives aux inondations,' Paris, 1872.

[4] See Login, *Nature*, i. pp. 629, 654; ii. p. 72.

[5] The brown colour of river or estuary water is not always due to mud. In the Southampton Water it is caused in summer by the presence of protozoa (*Peredinium fuscum*). A. Angell, *Brit. Assoc.* 1882, sects. p. 589.

and impart the characteristic turbidity to rivers; the coarser sand and gravel are driven along the river-bottom.[1]

The presence of a moving stratum of coarse detritus on the bed of a brook or river may be detected in transit, for though invisible beneath the overlying discoloured water, the stones of which it is composed may be heard knocking against each other as the current sweeps them onward. Above Bonn, and again a little below the Lurelei Rock, while drifting down the Rhine, the observer, by laying his ear close to the bottom of the open boat, may hear the harsh grating of the gravel-stones over each other, as the current pushes them onwards along the bottom. On the Moselle also, between Cochem and Coblentz, the same fact may be noticed.

The transporting capacity of a stream depends (*a*) on the volume and velocity of the current, (*b*) on the size, shape, and specific gravity of the sediment, and (*c*) partly on the chemical composition of the water. (*a*) According to the calculations of Hopkins,[2] the capacity of transport increases as the sixth power of the velocity of the current; thus the motive power of the current is increased 64 times by the doubling of the velocity, 729 times by trebling, and 4096 times by quadrupling it. If a stream which, in its ordinary state, can just move pebbles weighing an ounce, has its velocity doubled by a flood, it can then sweep forward stones weighing 4 lb. Mr. David Stevenson[3] gives the subjoined table of the power of transport of different velocities of river currents:—

In. per Second.		Mile per Hour.	
3	=	0·170	will just begin to work on fine clay.
6	=	0·340	will lift fine sand.
8	=	0·4545	will lift sand as coarse as linseed.
12	=	0·6819	will sweep along fine gravel.
24	=	1·3638	will roll along rounded pebbles 1 inch in diameter.
36	=	2·045	will sweep along slippery angular stones of the size of an egg.

It is not the surface velocity, nor even the mean velocity, of a river which can be taken as the measure of its power of transport, but the bottom velocity—that is, the rate at which the stream overcomes the friction of its channel. (*b*) The average specific gravity of the stones in a river ranges between two and three times that of pure fresh water; hence these stones when borne along by the river lose from a half to a third of their weight in air. Huge blocks which could not be moved by the same amount of energy applied to them on dry ground, are swept along when they have found their way into a strong river-current. The shape of the fragments greatly affects their portability, when they are too large and heavy to be carried in mechanical suspension. Rounded stones are of course most easily transported: flat and angular ones are moved with comparative difficulty (see p. 385). (*c*) Pure water will retain fine mud in suspension for a long time; but the introduction of mineral matter in solution diminishes its capacity to do so, probably by lessening the molecular cohesion of the liquid. Thus the mingling of salt with fresh water causes a rapid precipitation of the suspended mud (p. 398). Probably each variety of river-water has its own capacity for retaining mineral matter in suspension, so that the mere mingling of these varieties may be one cause of the precipitation of sediment.[1]

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[1] These operations of running water may be studied with great advantage on a small scale, where brooks descend from high grounds into valleys, rivers, or lakes. A single flood suffices for the transport of thousands of tons of stones, gravel, sand, and mud, even by a small streamlet. At Lybster, for example, on the coast of Caithness, as the author was informed by Mr. Thomas Stevenson, C.E., a small streamlet carries down annually into a harbour which has there been made, between 400 and 500 cubic yards of gravel and sand. A weir or dam has been constructed to protect the harbour from the inroad of the coarser sediment, and this is cleaned out regularly every summer. But by far the greater portion of the fine silt is no doubt swept out into the North Sea. The erection of the artificial barrier, by arresting the seaward course of the gravel, reveals to us what must be the normal state of this stream and of similar streams descending from maritime hills. The area drained by the stream is about four square miles; consequently the amount of loss of surface, which is represented by the coarse gravel and sand alone, is $\frac{1}{12000}$ of a foot *per annum*.

[2] *Q. J. Geol. Soc.* viii. p. xxvii.

[3] 'Canal and River Engineering,' p. 315. See also Thoulet, *Ann. des Mines*, 1884, p. 507.

Besides inorganic sediment, rivers sweep seaward the remains of land-animals and vegetation. The great rafts of the Mississippi and its tributaries are signal examples of this part of river-action. The Atchafalaya has been so obstructed by drift-wood as to be fordable like dry land, and the Red River for more than a hundred miles flows under a matted cover of dead and living vegetation. The Amazon, Ganges, and other tropical rivers furnish abundant examples of the transport of a terrestrial fauna and flora to the sea. Minute forms of life sometimes constitute a considerable proportion of the so-called "solid impurity" of river-water. The mud of the Ganges, for instance, is estimated to contain from 12 to 25 per cent of infusoria, and that of the Nile 4·6 to 10 per cent.

Beyond their ordinary powers of transport, rivers gain at times considerable additional force from several causes. Those liable to sudden and heavy falls of rain, or to a rapid augmentation of their volume by the quick melting of snow, acquire by flooding an enormous increase of transporting and excavating power. More work may thus be done by a stream in a day than could be accomplished by it during years of its ordinary condition.[2] Another cause of sudden increase in the efficacy of river-action is provided when, from landslips formed by earthquakes, by the undermining influence of springs, or otherwise, a stream is temporarily dammed back, and the barrier subsequently gives way. The bursting out of the arrested waters produces great destruction in the valley. Blocks as big as houses may be set in motion, and carried down for considerable distances. Again, the transporting power of rivers may be greatly augmented by frost (see *postea*, p. 415). Ice forming along the banks or on the bottom, encloses gravel, sand, and even blocks of rock, which, when thaw comes, are lifted up and carried down the stream. In the rivers of Northern Russia and Siberia, which, flowing from south to north, have the ice thawed in their higher courses before it breaks up farther down, much disaster is sometimes caused by the piling up of the ice, and then by the bursting of the impeded river through the temporary ice-barrier. In another way, ice sometimes vastly increases the destructive power of small streams, where avalanches or an advancing glacier cross a valley and pond back its drainage. The valley of the Dranse, in Switzerland, has several times suffered from this cause. In 1818, the glacier-barrier extended across the valley for more than half a mile, with a breadth of 600 and a height of 400 feet. The waters above the ice-dam accumulated into a lake containing 800,000,000 cubic feet. By a tunnel driven through the ice, the water was drawn off without desolating the plains below.

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[1] T. Sterry Hunt, *Proc. Boston Nat. Hist. Soc.* 1874; W. Durham, *Chem. News*, xxx. (1874), p. 57; xxxvii. (1878), p. 47; W. Ramsay, *Quart. Journ. Geol. Soc.* xxxii. (1876), p. 129; C. Barus, *Bull. U.S. Geol. Surv.* No. 36 (1886); Thoulet, *Ann. Mines*, xix. (1891), p. 5. In this last memoir M. Thoulet concludes as the result of his experiments that the precipitation of clays takes place in fresh water which has had an addition of ten per cent of sea-water (and consequently of density equal to 1·002) exactly as in pure sea-water, and that this observation furnishes a measure for determining the true limits of the ocean and the continents.

[2] The extent to which heavy rains can alter the usual characters of rivers is forcibly exemplified in Sir T. Dick Lauder's 'The Morayshire Floods.' In the year 1829 the rivers of that region rose 10, 18, and in one case even 50 feet above their common summer level, producing almost incredible havoc. See also G. A. Koch, "Ueber Murbruche in Tyrol," *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 97.

The amount of sediment borne downwards by a river is not necessarily determined by the carrying power of the current. The swiftest streams are not always the muddiest. The proportion of sediment is partly dependent upon the hardness or softness of the rocks of the channel, the number of tributaries, the nature and slope of the ground forming the drainage-basin, the amount and distribution of the rainfall, the size of the glaciers (where such exist) at the sources of the river, the chemical composition of the water, and probably other causes. A rainfall spread with some uniformity throughout the year may not sensibly darken the rivers with mud, but the same amount of fall crowded into a few days or weeks may be the means of sweeping a vast amount of earth into the rivers, and sending them down in a greatly discoloured state to the sea. Thus the rivers of India, swollen during the rainy season (sometimes by a rainfall of 25 inches in 40 hours, as at the time of the destructive landslip at Naini Tal in September 1880), become rolling currents of mud.[1]

The amount of mineral matter transported by rivers can be estimated by examining their waters at different periods and places, and determining their solid contents. A complete analysis should take into account what is chemically dissolved, what is mechanically suspended, and what is driven or pushed along the bottom. We have already dealt with the chemically dissolved ingredients. In determinations of the mechanically mixed constituents of river-water, it is most advantageous to obtain the proportion first by weight, and then from its average specific gravity to estimate its bulk as an ingredient in the water. According to experiments made upon the water of the Rhone at Lyons, in 1844, the proportion of earthy matter held in suspension was by weight $\frac{1}{17000}$. Earlier in the century the results of similar experiments at Arles gave $\frac{1}{7000}$ as the proportion when the river was low, $\frac{1}{250}$ during floods, and $\frac{1}{2000}$ in the mean state of the river. The greatest recorded quantity is $\frac{1}{45}$ by weight, which was found "when the river was two-thirds up, with a mean velocity of probably about 8 feet per second."[1] A. Guérard, who has more recently made observations at the mouth of this river, estimates the total annual discharge of sediment to amount to 23,540,000 cubic yards, or $\frac{1}{2100}$ of the volume of the water.[2] Lombardini gives $\frac{1}{300}$ as the proportion by volume of the sediment in the water of the Po. In the Vistula, according to Spittell, the proportion by volume reaches a maximum of $\frac{1}{48}$.[3] The Rhine, according to Hartsoeker, contains $\frac{1}{100}$ by volume as it passes through Holland, while at Bonn the experiments of L. Horner gave a proportion of only $\frac{1}{10000}$ by volume.[4] Stiefensand found that, after a sudden flooding, the water of the Rhine at Uerdingen contained $\frac{1}{1282}$ by weight. Bischof measured the quantity of sediment in the same river at Bonn during a turbid state of the water, and found the proportion to be $\frac{1}{4878}$ by weight, while at another time, after several weeks of continuous dry weather, and when the water had become clear and blue, he detected only $\frac{1}{57800}$.[5] In the Meuse, according to the experiments of Chandellon, the maximum of sediment in suspension in the month of December 1849 was $\frac{1}{2100}$, the minimum $\frac{1}{71420}$, and the mean $\frac{1}{10000}$.[6] In the Elbe, at Hamburg, the proportion of mineral matter in suspension and solution has been found by experiment to average about $\frac{1}{7400}$. The Danube, at Vienna, yielded to Bischof about $\frac{1}{4200}$ of suspended and dissolved matter.[7] The Durance has ordinarily a maximum of 30 grammes of sediment to one litre of water, or $\frac{1}{33}$ by weight. In exceptional floods it rises to 100 grammes per litre of water, or $\frac{1}{10}$ by weight. In extreme low water the proportion may sink to about $\frac{1}{1000}$; the average for nine years from 1867 to 1875 was about $\frac{1}{350}$.[8] The Garonne is estimated to contain perhaps $\frac{1}{100}$.[9] In the Avon, which falls into the Severn, the mean amount of suspended mud is estimated at $\frac{1}{370}$.[10] The observations of Mr. Everest upon the water of the Ganges show that, during the four months of flood in that river, the proportion of earthy matter is $\frac{1}{428}$ by weight, or $\frac{1}{856}$ by volume; and that the mean average for the year is $\frac{1}{510}$ by weight, or $\frac{1}{1021}$ by volume.[11] According to Mr. Login, the waters of the Irrawaddy contain $\frac{1}{1700}$ by weight of sediment during floods, and $\frac{1}{5725}$ during a low state of the river.[1] In the Yangtse the proportion of sediment by weight is estimated by Mr. H. B. Guppy at $\frac{1}{2188}$.[2] The amount in the water of the River Plate is computed to be $\frac{1}{7752}$ by weight.[3] The Nile has been estimated to contain 159 parts of solid material in every 100,000 parts of water.

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[1] In his journeys through equatorial Africa, Livingstone came upon rivers which appear usually to consist more of sand than of water. He describes the Zingesi as "a sand-rivulet in flood, 60 or 70 yards wide, and waist deep. Like all these sand-rivers, it is for the most part dry; but, by digging down a few feet, water is to be found which is percolating along the bed on a stratum of clay. In trying to ford it," he remarks, "I felt thousands of particles of coarse sand striking my legs, which gave me the idea that the amount of matter removed by every freshet must be very great. . . . These sand-rivers remove vast masses of disintegrated rock before it is fine enough to form soil. In most rivers where much wearing is going on, a person diving to the bottom may hear literally thousands of stones knocking against each other."

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[1] Surell, "Mémoire sur l'amélioration des embouchures du Rhône." Humphreys and Abbot, 'Report upon the Physics and Hydraulics of the Mississippi, 1861, p. 147.

[2] *Min. Proc. Inst. Civ. Engin.* lxxxii. (1884-85), p. 309.

[3] *Ibid.* p. 148.

[4] *Edin. New Phil. Journ.* xviii. p. 102.

[5] 'Chemical Geology,' i. p. 122.

[6] *Annales des Travaux publics de Belgique*, ix. 204.

[7] *Op. cit.* i. p. 130. More recent observations by Sir Charles Hartley show that the mean proportion of sediment by weight in the Danube water for ten years from 1862 to 1871 was $\frac{1}{3060}$, or (at specific gravity 1·9) $\frac{1}{5814}$ by volume.

[8] G. Wilson, *Min Proc. Inst. Civ. Engin.* li. (1877-8), p. 216.

[9] Baumgarten, cited by Réclus, 'La Terre.'

[10] T. Howard, *Brit. Assoc.* 1875, p. 179.

[11] *Journ. Asiatic Society of Calcutta*, March 1832.

With regard to the amount of coarser and heavier sediment pushed along the bottom of a river by the downward current, it is more difficult to obtain accurate measurements. But it must sometimes constitute a large proportion of the total bulk of solid material discharged into the sea. In the case of the Rhone, for example, it is concluded by M. Guérard, that the quantity of sand rolled along the bed of this river into the Mediterranean in the course of a year is much greater than the lighter matter held in suspension in the water, and that "when the river, on approaching the sea, is no longer confined by embankments, the greater part of its alluvium is rolled along its bed." In flood-time it is not uncommon for whole banks of sand to travel bodily down the river.[4]

The most extensive and accurate determinations yet made upon the physics and hydraulics of a river are those of the United States Government upon the Mississippi. As the mean of many observations carried on continuously at different parts of the river for months together, Humphreys and Abbot, the engineers charged with the investigation, found that the average proportion of sediment contained in the water of the Mississippi is $\frac{1}{1500}$ by weight or $\frac{1}{2900}$ by volume.[5] But besides the matter held in suspension, they observed that a large amount of coarse detritus is constantly being pushed along the bottom of the river. They estimated that this moving stratum carries every year into the Gulf of Mexico about 750.000,000 cubic feet of sand, earth, and gravel. Their observations led them to conclude that the annual discharge of water by the Mississippi is 19,500,000,000,000 cubic feet, and consequently that the weight of mud annually carried into the sea by this river must reach the sum of 812,500,000,000 pounds. Taking the total annual contributions of earthy matter, whether in suspension or moving along the bottom, they found them to equal a prism 268 feet in height with a base of one square mile.

The value of these data to the geologist consists mainly in the fact that they furnish him with materials for an approximate measurement of the rate at which the surface of the land is lowered by subaerial waste. This subject is discussed at p. 460.

2. *Excavating Power.*—It was a prominent part of the teaching of Hutton and Playfair, that rivers have excavated the channels in which they flow. Experience in all parts of the world has confirmed this doctrine. The mechanical erosive work of running water depends for its rate and character upon (*a*) the friction of the detritus driven by the current against the sides and bottom of a watercourse, modified by (*b*) the varying declivity and the geological structure of the ground.

(*a*) Driven downward by the descending water of a river, the loose grains and stones are rubbed against each other, as well as upon the rocky bed, until they are reduced to fine sand and mud, and the sides and bottom of the channel are smoothed, widened, and deepened. The familiar effect of running water upon fragments of rock, in reducing them to rounded pebbles, is expressed by the common epithet "water-worn." A stream which descends from high rocky ground may be compared to a grinding mill; large boulders and angular blocks of rock, disengaged by frosts, springs, and general atmospheric waste, fall into its upper end; fine sand and silt are discharged into the sea.

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[1] *Proc. Roy. Soc. Edin.* 1857.

[2] *Nature*, xxii. p. 486. According to Dr. A. Woeikoff, this estimate is much under the truth; xxiii. p. 9. See also *op. cit.* p. 584.

[3] G. Higgin, *Nature*, xix. p. 555.

[4] *Mem. Proc. Inst. Civ. Engin.* lxxxii. (1884-85), p. 309.

[5] 'Report,' p. 148. The specific gravity of the silt of the Mississippi is given as 1·9.

In the series of experiments already referred to (p. 377), Prof. Daubrée made fragments of granite and quartz to slide over each other in a hollow cylinder partially filled with water, and rotating on its axis with a mean velocity of 0·80 to 1 metre in a second. He found that after the first 25 kilometres (about 15½ English miles) the angular fragments of granite had lost $\frac{4}{10}$ of their weight, while in the same distance fragments already well rounded had not lost more than $\frac{1}{100}$ to $\frac{1}{400}$. The fragments rounded by this journey of 25 kilometres in a cylinder could not be distinguished either in form or in general aspect from the natural detritus of a river-bed. A second product of these experiments was an extremely fine impalpable mud, which remained suspended in the water several days after the cessation of the movement. During the production of this fine sediment, the water, even though cold, was found in a day or two to have acted chemically upon the granite fragments. After a journey of 160 kilometres, 3 kilogrammes (about 6½ lb. avoirdupois) yielded 3·3 grammes (about 50 grains) of soluble salts, consisting chiefly of silicate of potash. A third product was an extremely fine angular sand consisting almost wholly of quartz, with scarcely any felspar, nearly the whole of the latter mineral having passed into the state of clay. The sand grains, as they are continually pushed onward over each other upon the bottom of a river, become rounded as the larger pebbles do. But a limit is placed to this attrition by the size and specific gravity of the grains.[1] As a rule, the smaller particles suffer proportionately less loss than the larger, since the friction on the bottom varies directly as the weight and therefore as the cube of the diameter, while the surface exposed to attrition varies as the square of the diameter. Mr. Sorby, in calling attention to this relation, remarks that a grain $\frac{1}{10}$ of an inch in diameter would be worn ten times as much as one $\frac{1}{100}$ of an inch in diameter, and a pebble 1 inch in diameter would be worn relatively more by being drifted a few hundred yards than a sand grain $\frac{1}{1000}$ of an inch in diameter would be by being drifted for a hundred miles.[2] So long as the particles are borne along in suspension, they will not abrade each other, but remain angular. Prof. Daubrée found that the milky tint of the Rhine at Strasburg in the months of July and August was due, not to mud, but to a fine angular sand (with grains about $\frac{1}{20}$ millimetre in diameter) which constitutes $\frac{2}{100000}$ of the total weight of water. Yet this sand had travelled in a rapidly flowing tumultuous river from the Swiss mountains, and had been tossed over waterfalls and rapids in its journey. He ascertained also that sand-grains with a mean diameter of $\frac{1}{10}$ mm. will float in feebly agitated water; so that all sand of finer grain must remain angular. The same observer has noticed that sand composed of grains with a mean diameter of ½ mm., and carried along by water moving at a rate of 1 metre per second, is rounded, and loses about $\frac{1}{10000}$ of its weight in every kilometre travelled.[3]

The effects of abrasion upon the loose materials on a river-bed are but a minor part of the erosive work performed by the stream. A layer of débris, only the upper portion of which is pushed onward by the normal current, will protect the solid rock of the river-channel which it covers, but it is apt to be swept away from time to time by violent floods. Sand, gravel, and boulders, in those parts of a river-channel where the current is strong enough to keep them moving along, rub down the rocky bottom over which they are driven. As the shape and declivity of the channel vary constantly from point to point, with, at the same time, frequent changes in the nature of the rocks, this erosive action is liable to continual modifications. It advances most briskly in the numerous hollows and grooves along which chiefly these loose materials travel. Wherever an eddy occurs in which gravel is kept in gyration, erosion is much increased. The stones, in their movement, excavate a hole in the channel, while, as they themselves are reduced to sand and mud, or are swept out by the force of the current, their places are taken by fresh stones brought down by the stream (Fig. 115). Such *pot-holes*, as they are termed, vary in size from mere cup-like depressions to huge cauldrons or pools. As they often coalesce, by the giving way of the intervening walls between two or more of them, they materially increase the deepening of the river-bed.

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[1] 'Géologie Expérimentale,' p. 250 *et seq.*

[2] *Q. J. Geol. Soc.* xxxvi. p. 59.

[3] 'Géologie Expérimentale,' pp. 256, 258.

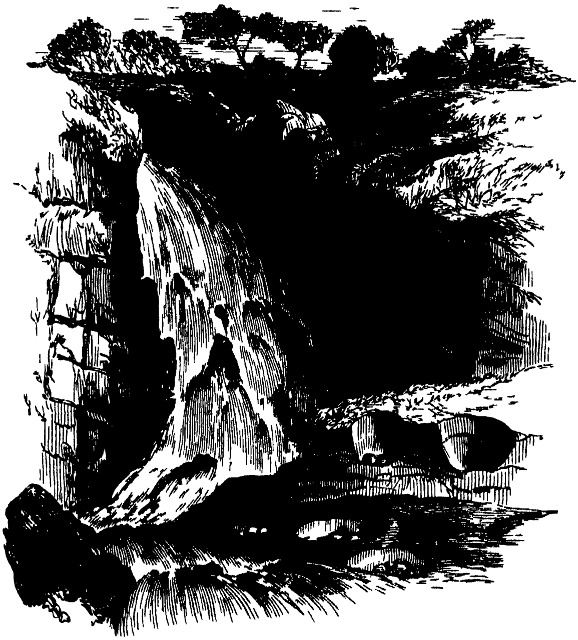

Fig. 115.—Rocky river channel with old Pot-holes.

That a river erodes its channel by means of its transported sediment and not by the mere friction of the water, is sometimes admirably illustrated in the course of streams filtered by one or more lakes. As the Rhone escapes from the Lake of Geneva, it sweeps with a swift clear current over ledges of rock that have not yet been very deeply eroded. The Niagara supplies a still more impressive example. Issuing from Lake Erie, and flowing through a level country for a few miles, it approaches its falls by a series of rapids. The water leaves the lake with hardly any appreciable sediment, and has too brief a journey in which to gather it, before beginning to rush down the rocky channel towards the cataract. The sight of the vast body of clear water, leaping and shooting over the sheets of limestone in the rapids, is in some respects quite as striking a scene as the great falls. To a geologist it is specially instructive; for he can observe that, notwithstanding the tremendous rush of water which has been rolling over them for so many centuries, these rocks have been comparatively little abraded. The smoothed and striated surface left by the ice-sheet of the Glacial Period can be traced upon them almost to the water's edge, and the flat ledges at the rapids are merely a prolongation of the ice-worn surface which passes under the banks of drift on either side. The river has hardly eroded more than a mere superficial skin of rock here since it began to flow over the glaciated limestone.

Similar evidence is offered by the St. Lawrence. This majestic river leaves Lake Ontario as pure as the waters of the lake itself. The ice-worn hummocks of gneiss at the Thousand Islands still retain their characteristic smoothed and polished surface down to and beneath the surface of the current. In descending the river, I was astonished to observe that the famous rapids of the St. Lawrence are actually hemmed in by islets and steep banks of boulder-clay, and not of solid rock. So little obvious erosion does the current perform, even in its tumultuous billowy descent, that a raw scar of clay betokening a recent slip is hardly to be seen. The banks are so grassed over, or even covered with trees, as to prove how long they have remained undisturbed in their present condition. That very considerable local destruction of these clay-islands, however, has been caused by floating ice will be alluded to further on.

Mere volume and rapidity of current, therefore, will not cause much erosion of the channel of a stream unless sediment be present in the water. A succession of lakes, by detaining the sediment, must necessarily enfeeble the direct excavating power of a river. On the other hand, by the disintegrating action of the atmosphere, and by the operations of springs and frosts, loose detritus as well as portions of the river-banks are continually being launched into the currents, which, as they roll along are thus supplied with fresh materials for erosion.

(*b*) Besides the obvious relation between the angle of slope of a river-bed and the scouring force of the river, a dominant influence, in the gradual excavation of a river-channel, is exercised by the lithological nature and geological structure of the rocks through which the stream flows. This influence is manifested in the form of the channel, the angle of declivity of its banks, and in the details of its erosion. On a small but instructive scale these phenomena are revealed in the operations of brooks. Thus, one of the most characteristic features of streams, whether large or small, is the tendency to wind in serpentine curves when the angle of declivity is low, and the general surface of the country tolerably level. This peculiarity may be observed in every stream which traverses a flat alluvial plain. Some slight weakness in one of its banks enables the current to cut away a portion of the bank at that point. By degrees a concavity is formed round which the upper water sweeps with increased velocity, while under-currents tend to carry sediment across to the opposite side. The outer bank is accordingly worn away, while the inner or concave side of the bend is not attacked, but is even protected by a deposit of sand or gravel.[1] Thus, bending alternately from one side to the other, the stream is led to describe a most sinuous course across the plain. By this process, however, while the course is greatly lengthened, the velocity proportionately diminishes, until, before quitting the plain, the stream may become a lazy, creeping current, in England commonly bordered with sedges and willows. A stream may eventually cut through the neck of land between two loops, as at *a*, *b*, and *c*, in Fig. 116, and thus for a while shorten its channel. Instances of this nature may frequently be observed in streams flowing through alluvial land. The old deserted loops[2] are converted, first into lakes, and by degrees into stagnant pools or bogs, until finally, by growth of vegetation and infilling of sediment by rain and wind, they become dry ground.

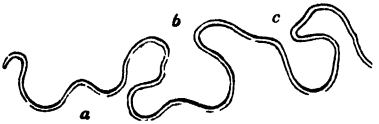

Fig. 116.—Meandering course of a brook.

Although most frequent in soft alluvial plains, serpentine water-courses may also be eroded in solid rock if the original form of the surface was tolerably flat. The windings of the gorges of the Moselle (Fig. 117) and Rhine through the table-land between Trèves, Mainz, and the Siebengebirge form a notable illustration.

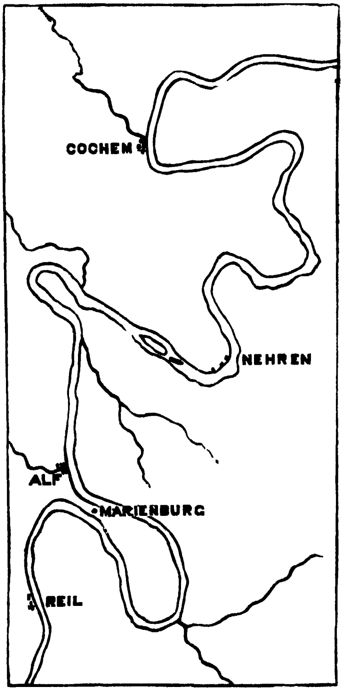

Fig. 117.—Windings of the gorge of the Moselle above Cochem.

Abrupt changes in the geological structure or lithological character of the rocks of a river-channel may give rise to waterfalls. In many cases, this feature of river-scenery has originated in lines of escarpment over which the water at first found its way, or in the same geological arrangement of hard and soft rocks by which the escarpments themselves have been produced. The occurrence of horizontal, tolerably compact strata, traversed by marked lines of joint, and resting upon softer beds, presents a structure well adapted for showing the part played by waterfalls in river-erosion. The waterfall acts with special potency against the softer underlying materials at its base. These are hollowed out, and as the foundations of the superincumbent more solid rocks are destroyed, slices of the latter from time to time fall off into the boiling whirlpool, where they are reduced to fragments, and carried down the stream. Thus the waterfall cuts its way backward up the stream, and as it advances it prolongs the excavation of the ravine into which it descends. The student will frequently observe, in the recession of waterfalls and consequent erosion of ravines, the important part taken by lines of joint in the rocks. These lines have often determined the direction of the ravine, and the vertical walls on either side depend for their precipitousness mainly upon these divisional planes in the rock.

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[1] J. Thomson, *Proc. Roy. Soc.* xxv. (1876), p. 5.

[2] "Aigues-mortes," or dead waters. See p. 403, *note*

The gorge of the Niagara affords a magnificent and remarkably simple illustration of these features of river-action. At its lower end, where it enters the wide plain that extends to Lake Ontario, there stretches away, on either side of the river, a line of cliff and steep wooded bank, formed by the escarpment of the massive Niagara limestone. Back from this line of cliff, through which it issues into the lacustrine plain, the gorge of the river extends for about 7 miles, with a width of from 200 to 400 yards, and a depth of from 200 to 300 feet. At the upper end lie the world-renowned falls. The whole of this great ravine has unquestionably been cut out by the recession of the falls. When the river first began to flow, it may have found the escarpment running across its course, and may then have begun the excavation of its gorge. More probably, however, the escarpment and waterfall began to arise simultaneously, and from the same geological structure. As the former grew in height, it receded from its starting point. The river-ravine likewise crept backward, but at a more rapid rate, and the result has been that while at present the cliff, worn down by atmospheric disintegration, stands at Queenstown, the ravine dug by the river extends 7 miles further inland. The waterfall will continue to cut its way back as long as the structure of the gorge continues as it is now—thick beds of limestone resting horizontally upon soft shales (Fig. 118). The softer strata at the base are undermined, and slice after slice is cut off from the cliff over which the cataract pours. The parallel walls of this great gorge owe their direction and mural character to parallel joints of the strata. The lesser or American fall (A in Fig. 119), enters by the side of the ravine and falls over its lateral wall. The larger or Canadian (Horse-shoe) fall (C) occupies the head of the ravine, and owes its form to the intersection of two sets of joints. The structure of the gorge being the same at both falls, it seems reasonable to infer that as the American fall, which appears to be diminishing in volume, has cut back only somewhere about 140 feet from the original face of the ravine, this branch of the river has, comparatively speaking, only recently begun to work. Goat Island, which now separates the two falls, is an outlier of drift resting on the limestone. It has been cut off from the rest of the ground on the right bank of the river by the branch which rejoins the main stream by the American fall. From the position of the glacial striæ it may be concluded that a great part, if not the whole, of the ravine has been excavated since the Glacial Period. There are indications, indeed, of a pre-glacial valley by which the waters of Lake Erie

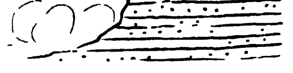

Fig. 118.—Section at the Horse-shoe Falls, Niagara.

a, Medina Sandstone, 300 feet; *b*, Clinton Limestone and Shale, 30 feet; *c*, Niagara Shale, 80 feet; *d*, Niagara Limestone, 165 feet, of which 85 feet are visible at the fall.

joined those of Ontario, before the erosion of the present gorge. Bakewell, from historical notices and the testimony of old residents, inferred that the rate of recession of the falls is three feet in a year. Lyell, on no better kind of evidence, concluded that "the average of one foot a year would be a much more probable conjecture," and estimated the length of time required for the excavation of the whole Niagara ravine at 35,000 years.[1] A commission recently appointed to survey the falls and to ascertain the rate of recession has reported (1890) that since 1742, when the first survey was made, the total mean recession of the Horse-shoe falls has been 104 feet 6 inches. The maximum recession at one point is 270 feet. The mean recession of the American falls is 30 feet 6 inches. The length of the crest has increased from 2260 to 3010 feet by the washing away of the embankment. The total area of recession of the American falls is 32,900 square feet, and that of the Horse-shoe falls 275,400 feet.

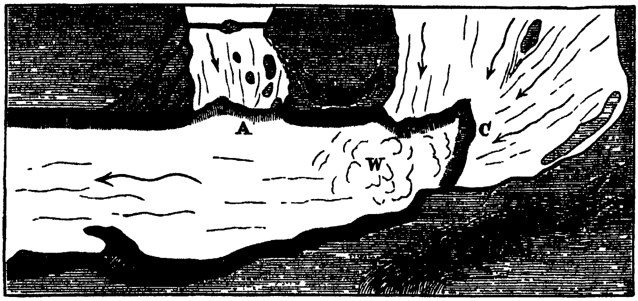

Fig. 119.—Plan of the Ravine of Niagara at the Falls.
A, American Fall; C, Canadian Fall; W, Whirlpool; G, Goat Island; D, Bank of Drift resting on ice-worn sheets of Limestone.

A feature of interest in the future history of the Niagara river deserves to be noticed here. It is evident that if the structure of the gorge continued the same from the falls to Lake Erie, the recession of the falls would eventually tap the lake, and reduce its surface to the level of the bottom of the ravine. Successive stages in this retreat of the falls are shown in Fig. 120, by the letters *f* to *n*, and in the consequent lowering of the lake by the letters *a*, *b* to *e*. It is believed, however, that a slight inclination of the strata carries the soft underlying shale out of possible reach of the fall, which will retard indefinitely the lowering of the lake.

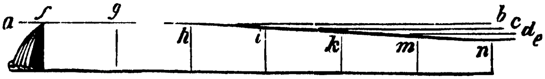

Fig. 120.—Section to illustrate the lowering of Lake Erie by the recession of Niagara Falls.

A waterfall may occasionally be observed to have been produced by the existence of a harder and more resisting band or barrier of rock crossing the course of the stream, as, for instance, where the rocks have been cut by an intrusive dyke or mass of basalt, or where, as in the case of the Rhine at Schaffhausen, and possibly in that of the Niagara, the stream has been diverted out of its ancient course by glacial or other deposits, so as to be forced to carve out a new channel, and rejoin its older one by a fall.[1] In these and all other cases, the removal of the harder mass destroys the waterfall, which, after passing into a series of rapids, is finally lost in the general abrasion of the river-channel.

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[1] Lyell, 'Travels in North America,' i. p. 32; ii. p. 93. 'Principles,' i. p. 358. Compare Lesley's 'Coal and its Topography' (1856), p. 169. On recent changes at the falls, see Marcou, *Bull. Soc. Géol. France* (2). xxii. p. 290. The Falls of St. Anthony on the Mississippi show, according to Winchell, a rate of recession varying from 3·49 to 6·73 feet per annum, the whole recession since the discovery of the falls in 1680 to the present time being 906 feet. *Q. J. Geol. Soc.* xxxiv. p. 899.

The resemblance of a deep narrow river-gorge to a rent opened in the ground by subterranean agency, has often led to a mistaken belief that such marked superficial features could only have arisen from actual violent dislocation. Even where something is conceded to the river, there is a natural tendency to assume that there must have been a line of fault and displacement as in Fig. 121, or at least a line of crack, and consequent weakness (Fig. 122). But the existence of an actual fracture is not necessary for the formation of a ravine of the first magnitude. The gorge of the Niagara, for example, has not been determined by any dislocation. Still more impressive proof of the same fact is furnished by the most marvellous river-gorges in the world—those of the Colorado region in North America. The rivers there flow in ravines thousands of feet deep and hundreds of miles long, through vast table-lands of nearly horizontal strata. The Grand Cañon (ravine) of the Colorado river is 300 miles long, and in some places more than 6000 feet in depth. In many instances there are two cañons, the upper being several miles wide, with vast lines of cliff-walls and a broad plain between them, in which runs the second cañon as another deep-gorge with the river winding over its bottom. The country is hardly to be crossed except by birds, so profoundly has it been trenched by these numerous gorges. Yet the whole of this excavation has been effected by the erosive action of the streams themselves.[2] Some idea of the vastness of the erosion of these plateaux may be formed from Fig. 123, the Frontispiece to this volume, and the illustrations in Book VII.

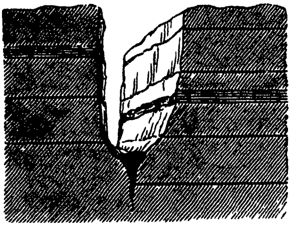

Fig. 121.—River-gorge in line of Fault.

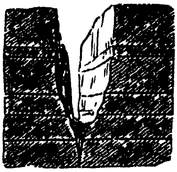

Fig. 122.—River-gorge in fissured strata.

In the excavation of a ravine, whether by the recession of a waterfall or of a series of rapids, the action of the river is more effective than that of the atmospheric agents. The sides of the ravine consequently retain their vertical character, which, where they coincide with lines of joint, is further preserved by the way in which atmospheric weathering acts along the joints. But where, from the nature of the ground or of the

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[1] Würtenberger, *Neues Jahrb.* 1871, p. 582.

[2] For descriptions and figures of this remarkable region, see Ives and Newberry, 'Explorations of the Colorado River of the West,' 1861; J. W. Powell, 'Exploration of the Colorado River of the West and its Tributaries,' 1875; Captain Dutton, 'Tertiary History of the Grand Cañon of the Colorado'; *Monograph II. U.S. Geological Survey*, 4to, 1882; and *postea*, Book VII.

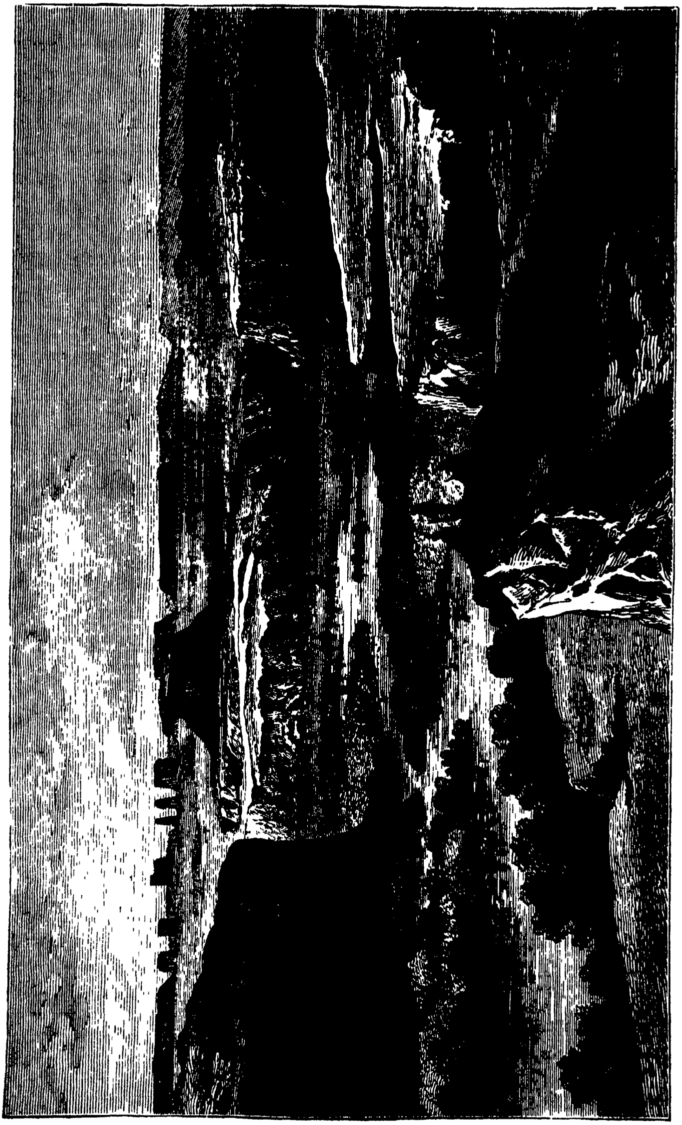

Fig. 123.—View of the erosion of the San Juan, Colorado Basin (Newberry).

climate, the denuding action of rain, frost, and general weathering is more rapid than that of the river, a wider and opener valley is hollowed out, through which the river flows, carrying away the materials washed into it from the surrounding slopes by rain and brooks.

3. *Reproductive Power.*—Every body of water which, when in motion, carries along sediment, drops it when at rest. The moment a current has its rapidity checked, it is deprived of some of its carrying power, and begins to lose hold upon its sediment, which tends more and more to sink and halt on the bottom the slower the motion of the water. In Fig. 124 the river in flowing from *a* to *b* has a less angle of declivity and a smaller transporting power, and will therefore have a greater tendency to throw down sediment, than in descending the steeper gradient from *b* to *c*.

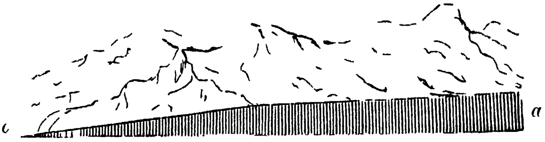

Fig. 124.—Section of part of a river channel (B.)

In the course of every brook and river, there are frequent checks to the current. If these are examined, they will usually be found to be each marked by a more or less conspicuous deposit of sediment. We may notice seven different situations in which stream-deposits or *alluvium* may be accumulated.

(*a*) At the foot of Mountain Slopes.—When a runnel or torrent descends a steep declivity it tears down the soil and rocks, cutting a gash out of the side of the mountain (Fig. 125). On reaching the more level ground at the base of the slope, the water, abruptly checked in its velocity, at once drops its coarser sediment, which gathers in a fan-shaped pile or cone ("*cone de déjection*", "*Murbruche*"[1]), with the apex pointing

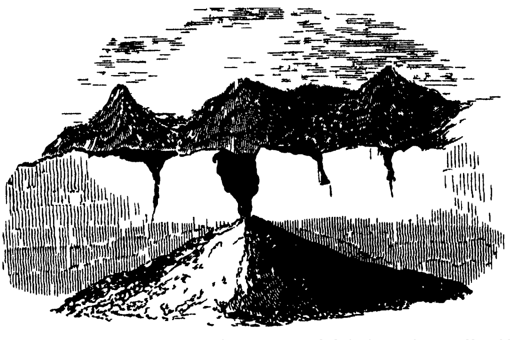

Fig. 125. Tributary torrent sending a cone of detritus into a valley (B.)

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[1] G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 97, describes the debacles of the Tyrol. Consult also the work of Surell and Cézanne cited on p. 372.

up the water-course. Huge accumulations of boulders and shingle may thus be seen at the foot of such torrents,—the water flowing through them, often in several channels which re-unite in the plain beyond. From the deposits of small streams, every gradation of size may be traced up to huge fans many miles in diameter and several hundred feet thick, such as occur in the upper basin of the Indus[1] and on the flanks of the Rocky Mountains,[2] as well as other ranges in North America (Fig. 126).[3] The level of the valleys in the Tyrol has been sensibly raised within historic times by the detritus swept into them from the surrounding mountains. Old churches and other buildings are half-buried in the accumulated sediment.[4]

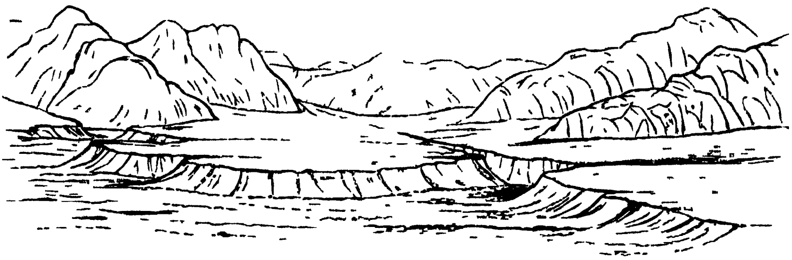

Fig. 126.—Fans of Alluvium Madison River, Montana.

(*b*) In River-beds.—The deposition of alluvium on river-beds is characteristically shown by the accumulation of sand or shingle at the concave side of each sharp bend of a river-course. While the main upper current is making a more rapid sweep round the opposite bank, under-currents pass across to the inner side of the curve and drop their freight of loose detritus, which, when laid bare in dry weather, forms the familiar sand bank or shingle-beach. Again, when a river, well supplied with sediment, leaves mountainous ground where its course has been rapid, and enters a region of level plain, it begins to drop its burden on the channel, which is thereby heightened, till it may actually rise above the level of the surrounding plains (Fig. 127).

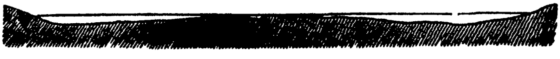

Fig. 127.—Section of a River-plain, showing heightening of channel by deposits of sediment (*B.*)

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[1] On the alluvial deposits of this region, see Drew, *Q. J. Geol. Soc.* xxix. p. 441; also his 'Jummoo and Kashmere Territories,' 1875.

[2] See Dutton's 'High Plateaux of Utah.' Hayden's 'Reports of the U.S. Geological and Geographical Surveys of the Territories.'

[3] In the great inland basin of North America, which includes the arid tracts of Great Salt Lake and other saline waters, the depth of accumulated detritus must amount in many places to several thousand feet. See on this subject I. C. Russell, *Geol Mag.* 1889, and Gilbert's Essay on Lake-Shores in the *5th Annual Report of the U.S. Geol. Surv*

[4] G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 123.

This tendency is displayed by the Adige, Reno, and Brenta, which, descending from the Alps well supplied with detritus, debouch on the plains of the Po.[1] The Po itself has been quoted as an instance of a river continuing to heighten its bed, while man in self-defence heightens its embankments, until the surface of the river becomes higher than the plains on either side. It has been shown by Lombardini, however, that the bed of this river has undergone very little change for centuries; that only here and there does the mean height of the water rise above the level of the plains, being generally considerably below it, and that even in a high flood the surface of the river is scarcely ten feet above the pavement in front of the Palace at Ferrara.[2] The Po and its tributaries have been carefully embanked, so that much of the sediment of the rivers, instead of accumulating on the plains of Lombardy, as it naturally would do, is carried out into the Adriatic. Hence, partly, no doubt, the remarkably rapid rate of growth of the delta of the Po. But in such cases, man needs all his skill and labour to keep the banks secure. Even with his utmost efforts, a river will now and then break through, sweeping down the barrier which it has itself made, as well as any additional embankments constructed by him, and carrying its flood far and wide over the plain. Left to itself, the river would incessantly shift its course, until in turn every part of the plain had been again and again traversed. It is indeed in this way that a great alluvial plain is gradually levelled and heightened. The most stupendous example of the gradual heightening of a plain by river deposits, and of the devastation caused by the bursting of the artificial barriers raised to control the stream, is that of the Hoang Ho or Yellow River. So frequently has this river changed its course across the great eastern plain, and so appalling has been the consequent devastation, that it has received the name of "China's sorrow." The last great inundation took place in the autumn of 1887, when hundreds of villages were submerged and more than a million human beings were drowned. Breaking down its frail embankment, the stream poured through the breach, which was some 1200 yards wide, and spread out over a width of 30 miles in a current ten to twenty feet deep in the middle.

(*c*) On River-banks and Flood-plains.—As is partly implied in the action described in the foregoing paragraph, alluvium is laid down on the level tracts or flood-plain over which a river spreads in flood. It consists usually of fine silt, mud, earth, or sand; though close to the channel, it may be partly made up of coarser materials. When a flooded river overflows, the portions of water which spread out on the plains, by losing velocity, and consequently power of transport, are compelled to let fall more or less of their mud and sand. If the plains happen to be covered with wood, bushes, scrub, or tall grass, the vegetation acts the part of a sieve, and filters the muddy water, which may rejoin the main stream comparatively clear. The height of the plain is thus increased by every flood, until, partly from this cause and partly, in the case of a rapid stream, from the erosion of the channel, the plain can no longer be overspread by the river. As the channel is more and more deepened, the river continues, as before, to be liable, from inequalities in the material of its banks, sometimes of the most trifling kind, and from the behaviour of water flowing in irregular channels, to wind from side to side in wide curves and loops, and cuts into its old alluvium, making eventually a newer plain at a lower level. Prolonged erosion carries the channel to a still lower level, where the stream can attack the later alluvial deposit, and form a still lower and newer one. The river comes by this means to be fringed with a series of terraces (Fig. 128), the surface of each of which represents a former flood-level of the stream.

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[1] It is in the north of Italy that the struggle between man and nature has been most persistently waged. See Lombardini, in *Ann. des Ponts-et-Chaussées*, 1847. Beardmore's 'Tables,' p. 172. The bed of the Yang-tse-Kiang has been raised in places far above the level of the surrounding country by embanking. E. L. Oxenham, *Journ. Geog. Soc.* xlv. (1875), p. 182.

[2] Between Mantua and Modena the Po is said to have raised its bed more than 5½ metres since the 15th century. Dausse, *Bul. Soc. Géol. France*, iii. (3me sér.), p. 137.

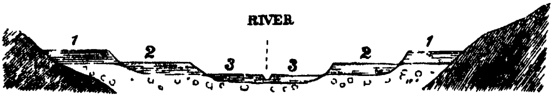

Fig. 128.—Section of River-terraces.

In Britain, it is common to find three such terraces, but sometimes as many as six or seven or even more may occur. On the Seine and other rivers of the North of France, there is a marked terrace at a height of 12 to 17 metres above the present water-level. In North America, the river-terraces exist on so grand a scale that the geologists of that country have named one of the later periods of geological history, during which those deposits were formed, the *Terrace Epoch* (Fig. 129). The modern alluvium of the Mississippi, from the mouth of the Ohio to the Gulf of Mexico, covers an area of 19,450 miles, and has a breadth of from 25 to 75 miles and a depth of from 25 to 40 feet. The old alluvium of the Amazon likewise forms extensive lines of cliff for hundreds of miles, beneath which a newer platform of detritus is being formed.[1]

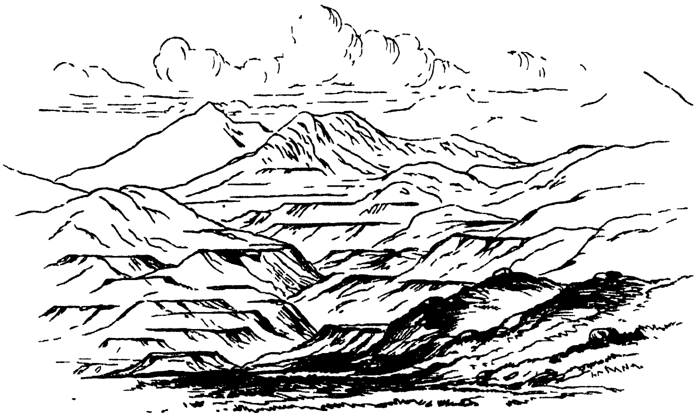

Fig. 129.—Old Terraces on the left bank of the Yellowstone River, above the first Cañon. Montana.

In the attempt to reconstruct the history of the old river-terraces of a country, we have to consider whether they have been entirely cut out of older alluvium (in which case, of course, the valleys must have been deeper and broader than now, before the formation of the terraces, Fig.

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[1] The stages of terrace-making in the régime of a great river are well brought out in the case of the Amazon. C. B. Brown, *Q. J. Geol. Soc.* xxxv. p. 763. The subject of the origin of river-terraces is discussed by Mr. H. Miller of the Geological Survey in *Proc. Roy. Phys. Soc. Edin.* 1883, p. 263.

128); whether they afford any indications of having been formed during a period of greater rainfall, when the rivers were larger than at present; whether they point to upheaval of the interior of the country, which would accelerate the erosive action of the streams, or to depression of the interior or rise of the seaward tracts, which would diminish that action and increase the deposition of alluvium. Professor Dana has connected the terraces of America with the elevation of the axis of that continent. There can be no doubt that both in Europe and North America the rivers at a comparatively recent geological period had a much greater volume than they now possess.

(*d*) In Lakes.—When a river enters a lake or inland sea its current is checked, and its sediment begins to spread in fan-shape over the bottom (*c* in Fig. 130). Every tributary stream brings in its contribution of detritus. In this way, a series of shoals is pushed out into the lake (Fig. 131 and p. 406). This phenomenon may frequently be instructively observed from a height overlooking a small lake among mountains. At the mouth of each torrent or brook lies a little tongue of its alluvium (a true *delta*), through which the streamlet winds in one or more branches, before mingling its waters with those of the lake. Two streams entering from opposite sides (as at *c*, *d* Fig. 131) may join their alluvia and divide a lake into two, like the once united lakes of Thun and Brienz at Interlaken. Or, by the advance of the alluvial deposits, the lake may be finally filled up altogether, as has happened in innumerable cases in all mountainous countries (Fig. 132).

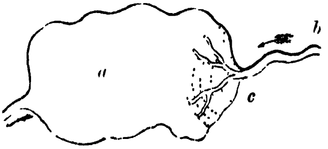

Fig. 130.—Streamlet (*b*) entering a small lake (*a*), and depositing a fan of sediment (*c*).

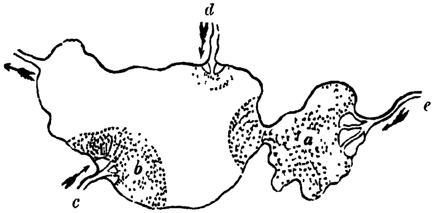

Fig. 131.—Plan of a lake entered by three streams (*c*, *d*, *e*), each of which deposits a cone of sediment (*a*, *b*) at its mouth

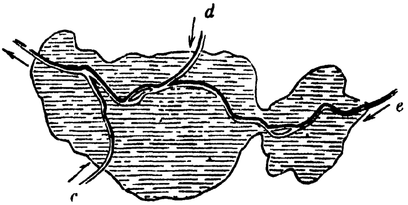

Fig. 132.—Lake (as in Fig. 131) filled up and converted into an alluvial plain by the three streams, *c*, *d*, *e*.

The rapidity of the infilling is sometimes not a little remarkable. Since the year 1714, the Kander is said to have thrown into the Lake of Thun a delta measuring 230 acres, now partly woodland, partly meadow and marsh. The Aar, at its entrance into the Lake of Brienz, has deposited a delta 3500 to 4000 feet broad, formed of detritus which at the mouth of the river has an outward slope of 30°, that gradually falls to the nearly level lake floor. In twenty-seven years after its rectification the Reuss had laid down in the Lake of Lucerne a delta estimated to contain upwards of 141 million of cubic feet of sediment, which is equivalent to a discharge of 19,350 cubic feet in a day, or nearly 7,000,000 cubic feet in a year.[1]

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[1] A. Heim, *Jahrb. Schweizer Alpenklubs*, 1879.

In the case of a large lake whose length is great in proportion to the volume of the tributary river, the whole of the detritus may be deposited, so that, at the outflow, the river becomes as clear as when its infant waters began their course from the springs, snows, and mists of the far mountains. Thus, the Rhone enters the Lake of Geneva turbid and impetuous, but escapes at Geneva as blue translucent water. Its sediment is laid down on the floor of the lake, and chiefly at the upper end, as an important delta which quite rivals that of a great river in the sea. Hence, lakes act as filters or sieves to intercept the sediment which is travelling in the rivers from the high grounds to the sea (p. 405).[1]

(*e*) Estuarine Deposits; Bars and Lagoon-barriers.—If we take a broad view of terrestrial degradation, we must admit that the deposit of any sediment on the land is only temporary; the inevitable destination of all detrital material is the floor of the sea. Where a gently flowing river comes within the influence of the alternate rise and fall of the tides, a new set of conditions is established in regard to the disposal of the sediment. During the flow of the tide in the Severn, for example, the suspended mud is carried up the estuary, and sometimes far up its tributaries. For two-thirds of the ebb, though the surface-water is running out rapidly, the bottom-water is practically at rest: only during the remaining third of the ebb does the bottom-water flow outwards and with sufficient velocity to scour the channel. But this lasts for so short a time that it hardly removes as much mud or sand as has been laid down during flood and the earlier part of ebb-tide. Hence the sediment is in a state of continual oscillation upward and downward in the estuary. At the lower end, some portion of it is continually being swept out to sea. At the upper end, fresh material of similar kind is being supplied by the river. But, between these two limits, the same sediment may be kept in suspension or may be alternately deposited and removed for many weeks or months before it finally escapes to sea and is spread out on the bottom. To this cause, doubtless, the remarkable turbidity of many estuaries is to be attributed.[2]

Where a river, with a considerable velocity of current, enters the sea, its mouth is commonly obstructed by a bar of gravel, sand, or mud. The formation of this barrier results from the conflict between the river and the ocean. The muddy fresh water floats on the heavier salt water, its current is lessened, and it can no longer push along the mass of detritus at the bottom, which therefore accumulates and tends to form a bar. Moreover, as already mentioned (p. 381), though fresh water can for a long time retain fine mud in suspension, this sediment is rapidly thrown down when the fresh is mixed with saline water. Hence, apart from the necessary loss of transporting power by the checking of the current at the river-mouth, the mere mingling of a river with the sea must of itself be a cause of the deposit of sediment. Moreover, in many cases the sea itself piles up great part of the sand and gravel of

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[1] Consult a suggestive essay, G. K. Gilbert on the topographic features of lake-shores, *5th Ann. Rep. U.S. Geol. Surv.* 1885, p. 75.

[2] See an interesting paper by Prof. Sollas, *Q. J. Geol. Soc.* xxxix. (1883), p. 611, and authorities there cited.

the bar. Heavy river-floods push the bar further to sea, or even temporarily destroy it; storms from the sea, on the other hand, drive it further up the stream.

Some of these facts in the economy of rivers have been well studied at the mouths of the Mississippi. At the south-west pass, the bar is equal in bulk to a solid mass one mile square and 490 feet thick, and advances at the rate of 338 feet each year. It is formed where the river water begins to ascend over the heavier salt water of the gulf, and consists mainly of the sediment that is pushed along the bed of the river. A singular feature of the Mississippi bars is the formation upon them of "mud lumps." These are masses of tough clay, varying in size from mere protuberances like tree-trunks, up to islands several acres in extent. They rise suddenly, and attain heights of from 3 to 10, sometimes even 18 feet above the sea-level. Salt springs emitting inflammable gas rise upon them. After the lapse of a considerable time, the springs cease to give off gas, and the lumps are worn away by the currents of the river and the gulf. The origin of these excrescences has been attributed to the generation of carburetted hydrogen by the decomposing vegetable matter in the sediment underlying the tenacious clay of the bars.[1]

Conspicuous examples of the formation of detrital bars may occasionally be observed at the mouths of narrow estuaries, as at *e* in Fig. 133. A constant struggle takes place in such situations between the tidal currents and waves which tend to heap up the bar and block the entrance to the estuary, and the scour of the river and ebb-tide which endeavours to keep the passage open.

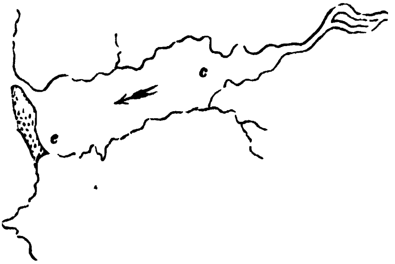

Fig. 133.—Shingle and sand-spit (*e*) at the mouth of an estuary (*c*), entered by a river, and opening upon an exposed rocky coast-line (*B*.)

Another remarkable illustration of the contest between alluvium-carrying streams and the land-eroding ocean is shown by the vast lines of bar or bank which stretch along the coasts both of the Old and the New World. The streams do not flow straight into the sea, but run sometimes for many miles parallel to the shore-line, accumulating behind the barriers into broad and long lagoons, but eventually breaking through the barriers of alluvium and entering the sea. On a small scale, examples occur on the coasts of the British Islands, as at Start Bay, Devon (Fig. 134), where the slates (*e*) with their weathered surface (*d*) are flanked by a fresh-water lake (*c*), ponded back by a bar (*b*) from the sea (*a*). The lagoons of the shores of the Mediterranean,[2] and the Kurische and Frische Haf in the Baltic, near Dantzic, are familiar examples. A conspicuous series of these alluvial bars fronts the American mainland for many hundred miles round the Gulf of Mexico and the shores of Florida, Georgia, and North Carolina (Fig. 135).[3] A space of several

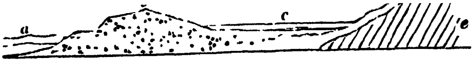

Fig. 134.—Section of bar and lagoon. Slapton Pool, Start Bay, Devon (*B*.)

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[1] Humphreys and Abbot, 'Report on Mississippi River,' 1861, p. 452.

[2] For an account of these see Ansted, *Min. Proc. Inst. Civ. Engin.* xxviii. (1869), p. 287.

[3] See Report by H. D. Rogers, *Brit. Assoc.* iii. p. 13.

hundred miles on the east coast of India is similarly bordered. Élie de Beaumont, indeed, estimated that about a third of the whole of the coast-lines of the continents is fringed with such alluvial bars.[1]

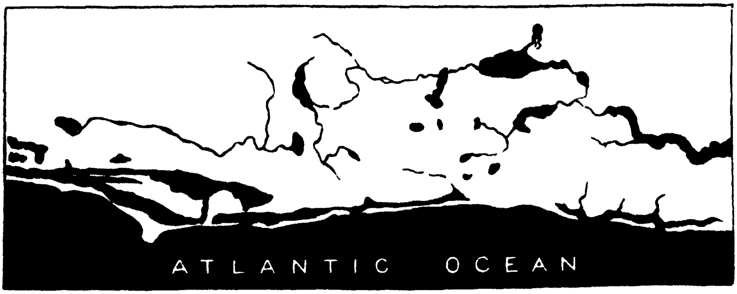

Fig. 135.—Plan of coast-bars and lagoons Coast of Florida.

On a coast-line such as that of Western Europe, subject both to powerful tidal action and to strong gales of wind, many interesting illustrations may be studied of the struggle between the rivers and the sea, as to the disposal of the sediment borne from the land. De la Beche described an example from the coast of South Wales where two streams, the Towey and Nedd (*a* and *b*, Fig 136), enter Swansea Bay, bearing with them a considerable amount of sandy and muddy sediment. The fine mud is carried by the ebb-tide (*t t t*) into the sheltered bay between Swansea (*c*) and the Mumble Rocks (*e*) but is partly swept round this headland into the Bristol Channel. The coarser sandy sediment, more rapidly thrown down, is stirred up and driven shorewards by the breakers caused by the prevalent west and south-west winds (*w*). The sandy flats thereby formed are partly uncovered at low water, and being then dried by the wind, supply it with the sand which it blows inland to form the lines of sand-dunes (*f f*).[2]

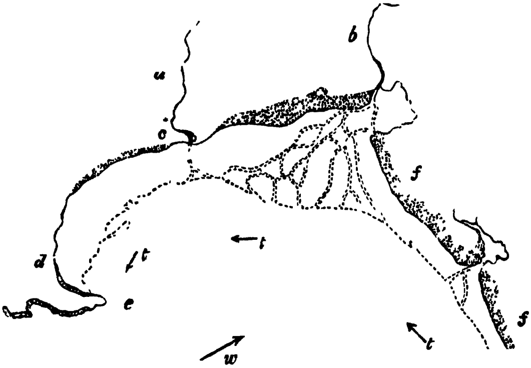

Fig. 136.—Action of rivers, tides, and winds in Swansea Bay (*B.*)

(*f*) Deltas in the Sea.—The tendency of sediment to accumulate in a tongue of flat land when a river loses itself in a lake, is exhibited on a vaster scale where the great rivers of the continents enter the sea. It was to one of these maritime accumulations, that of the Nile, that the Greeks gave the name delta, from its resemblance to their letter Δ, with the apex pointing up the river, and the base fronting the sea. This shape being the common one in all such alluvial deposits at river mouths, the term delta has become their general designation. A delta consists of successive layers of detritus, brought down from the land and spread out at the mouth of a river, until they reach the surface, and then, partly by growth of vegetation and partly by flooding of the river, form a plain, of which the inner and higher portion comes eventually to be above the reach of floods. Large quantities of drift-wood are often carried down, and bodies of animals are swept off to be buried in the delta, or even to be floated out to sea. Hence, in deposits formed at the mouths of rivers, we may always expect to find terrestrial organic remains.

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[1] 'Leçons de Géologie pratique,' i. p. 249. In this volume some interesting examples of this kind of deposit are described.

[2] 'Geological Observer,' p. 88.

A delta does not necessarily form at every river-mouth, even where there is plenty of sediment. In particular, where the coast-line on either side is lofty, and the water deep, or where the coast is swept by powerful tidal currents, there is no delta.[1] In some cases, too, the sediment spreads out over the sea-bottom without being allowed by the sea to build itself up into land, as happens at the mouths of some of the rivers in the north-west of France. Considerable influence may be exerted by tides and currents in arresting or facilitating the spread of sediment over the sea-floor. The deltas of the Rhone, Nile, Tiber, and Danube are formed in tideless or nearly tideless seas.[2]

When a river enters upon the delta portion of its course, it assumes a new character. In the previous parts of its journey it is augmented by tributaries; but now it begins to split up into branches, which wind to and fro through the flat alluvial land, often coalescing and thus enclosing insular spaces of all dimensions. The feeble current, no longer able to bear along all its weight of sediment, allows much of it to sink to the bottom and to gather over the tracts which are from time to time submerged. Hence many of the channels are choked up, while others are opened out in the plain, to be in turn abandoned; and thus the river restlessly shifts its channels. The seaward ends of at least the main channels grow outwards by the constant accumulation of detritus pushed into the sea, unless this growth chances to be checked by any marine current sweeping past the delta.

These features are nowhere more strikingly displayed than by the great delta of the Mississippi (Fig. 137). The area of this vast expanse of alluvium is given at 12,300 square miles, advancing at the rate of 262 feet yearly into the Gulf of Mexico at a point which is now 220 miles from the head of the delta.[3] On a smaller scale the rivers of Europe furnish many excellent illustrations of delta-growth. Thus the Rhine, Meuse,

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[1] Consult Admiral Spratt's memoir, 'An investigation of the effect of the prevailing wave influence on the Nile's deposit,' folio, London, 1859.

[2] For a discussion on non-tidal rivers, see *Min. Proc. Inst. Civ. Engin.* lxxxii. (1885), pp. 2-68, where information is given about the Tiber and some other rivers.

[3] Humphreys and Abbot, *op. cit.*; see also C. Hartley, *Min. Proc. Inst. Civ. Engin.* xl. p. 185. The tide has a mean rise of 15 inches every 24 hours at the Mississippi mouths.

Sambre, Scheldt, and other rivers have formed the wide maritime plain of Holland and the Netherlands. The Rhone, which has deposited an important delta in the Mediterranean Sea, is computed to furnish every year (by the Petit Rhône) about four millions of cubic metres of sediment to the shores.[1] The upper reaches of the Adriatic Sea are being so rapidly shallowed and filled up by the Po, Adige, and other streams, that Ravenna, originally built in a lagoon like Venice, is now 4 miles from the sea; and the port of Adria, so well known in ancient times as to have given its name to the Adriatic, is now 14 miles inland, while on other parts of that coast-line the breadth of land gained within the last 1800 years has been as much as 20 miles. Borings for water near Venice to a depth of 572 feet have disclosed a succession of nearly horizontal clays, sands, and lignitiferous beds. Marine shells (*Cardium*, &c.) occur in the sandy layers; the lignites and lignitiferous clays contain land-vegetation and terrestrial shells (*Succinea*, *Pupa*, *Helix*), the whole succession of deposits indicating an alternation of marine and terrestrial or fresh-water conditions.[2] On the opposite side of the Italian peninsula, great additions have been made to the coast-line within the historical period. It is computed that the Tuscan rivers lay down as much as 12 million cubic yards of sediment every year within the marshes of the Maremma. The "yellow" Tiber, as it was aptly termed by the Romans, owes its colour to the abundance of the sediment which it carries to sea. It has long been adding to the coast-line around its mouth at the rate of from 12 to 13 feet per annum. The ancient harbour of Ostia is now consequently more than 3 miles inland. Its ruins have been partially excavated, but every flood of the river leaves a thick deposit of mud on the streets and on the floors of the uncovered houses. Hence it would seem that the Tiber has not only advanced its coast-line but has raised its bed on the plains, by the deposit of alluvium, so that it now overflows places which, 2000 years ago,

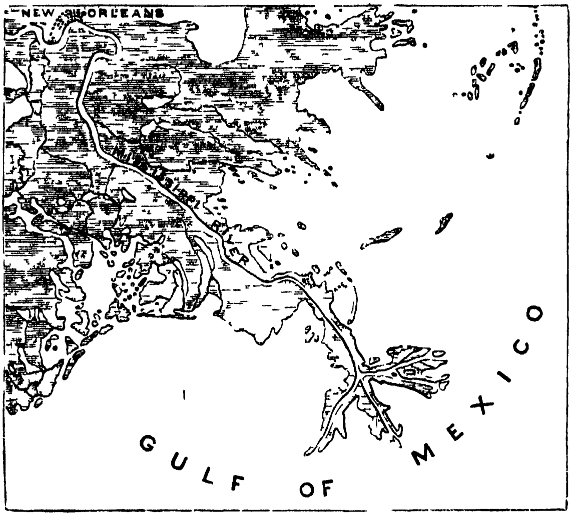

Fig. 187 — Map of Delta of Mississippi.

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[1] For this delta and its lagoons, see the paper by Ansted, quoted *ante*, p. 399. Reclus, "Géographie Universelle," tome ii. (France), chaps. ii. and iii., and A. Guérard, *Min. Proc. Inst. Civ. Engin.* lxxxii. (1884-85), p. 305.

[2] Élie de Beaumont, 'Leçons de Geologie pratique,' i. p. 323. *Geol. Mag.* ix. (1872), p. 486.

could not have been so frequently under water.[1] In the Black Sea, a great delta is rapidly growing at the mouths of the Danube. At the Kilia outlets the water is shallowing so fast that the lines of soundings of 6 feet and 30 feet are advancing into the sea at the rate of between 300 and 400 feet per annum.[2] The typical delta of the Nile has a seaward border 180 miles in length, the distance from which to the apex of the plain where the river bifurcates is 90 miles.[3] The united delta of the Ganges and Brahmaputra (Fig. 138) covers a space of between 50,000 and 60,000 square miles, and has been bored through to a depth of 481 feet, the whole mass of deposits consisting of fine sands and clays, with occasional pebble-beds, a bed of peat and remains of trees, but with no trace of any marine organism.[4]

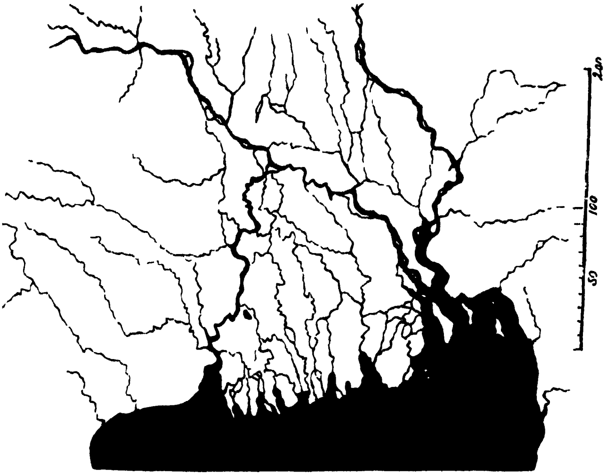

Fig. 138.—Delta of the Ganges and Brahmaputra (with Scale of Miles).

(*g*) Sea-borne Sediment.—Although more properly to be noticed under the section on the Sea, the final course of the materials worn by rains and rivers from the surface of the land may be referred to here. By far the larger part of these materials sinks to the bottom close to the land. It is only the fine mud carried in suspension in the water which is carried out to sea. In none of the numerous soundings and dredgings in the Gulf of Mexico has Mississippi mud been obtained from the bottom more than 100 miles eastward from the mouth of the river.[1] The soundings taken by the *Challenger*, however, brought up land-derived detritus from depths of 1500 fathoms—200 miles or more from the nearest shores (p. 455). The sea fronting the Amazon is sometimes discoloured for 300 miles by the mud of that river.

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[1] See an interesting article by Professor Charles Martins on the Aigues-Mortes (*i.e.* dead waters or disused river-channels), in *Revue des Deux Mondes*, 1874, p. 780. I accompanied the distinguished French geologist on the occasion of his visit to Ostia in the spring of 1873, and was much struck with the proofs of the rapidity of deposit in favourable situations. In the article just cited, and in another in *Comptes rend.* lxxviii. p. 1748, some valuable information is given regarding the progress of the delta of the Rhone in the Mediterranean. Interesting historical data as to geological changes at the mouths of the Rhine, Meuse, Elbe, Po, Rhone, and other European rivers, as well as of the Nile, will be found in Élie de Beaumont's 'Leçons de Géologie pratique,' vol. i. p. 253.

[2] Hartley, *Min. Proc. Inst. Civ. Engin.* xxxvii. p. 216.

[3] For a detailed study of the Nile delta in its geological aspects, see an essay by Dr. J. Jankó, *Mittheil. Jahrb. Kön. Ungarischen Geol. Anst.* viii. (1890), p. 236.

[4] For a full account of the alluvium of the Indo-Gangetic plain, see Medlicott and Blanford's 'Geology of India,' chap. xvii., and authorities there cited; also a more recent paper by Mr. Medlicott, *Records Geol. Surv. India* 1881, p. 220.

§ 4. Lakes.

Depressions filled with water on the surface of the land, and known as Lakes, occur abundantly in the northern parts of both hemispheres, and more sparingly, but often of large size, in warmer latitudes. For the most part, they do not belong to the normal system of erosion in which running water is the prime agent, and to which the excavation of valleys and ravines must be attributed. On the contrary, they are exceptional to that system, for the constant tendency of running water is to fill them up. Their origin, therefore, must be sought among some of the other geological processes. (See Book VII.)

Lakes are conveniently classed as fresh or salt. Those which possess an outlet contain in almost all cases fresh water; those which have none are usually salt.

1. **Fresh-water Lakes.**—In the northern parts of Europe and America, as first emphasised by Sir Andrew C. Ramsay, lakes are prodigiously abundant on ice-worn rock-surfaces, irrespective of dominant lines of drainage. They seem to be distributed as it were at random, being found now on the summits of ridges, now on the sides of hills, and now over broad plains. They lie for the most part in rock-basins, but many of them have barriers of detritus. Their connection with the operations of the glacial period will be afterwards alluded to. In the mountainous regions of temperate and polar latitudes, lakes abound in valleys, and are connected with main drainage-lines. In North America and in Equatorial Africa, vast sheets of fresh water occur in depressions of the land, and are rather inland seas than lakes.

The water of many lakes has been observed to rise above its normal level for a few minutes or for more than an hour, then to descend beneath that level, and to continue this vibration for some time. In the Lake of Geneva, where these movements, locally known there as *Seiches*, have long been noticed, the amplitude of the oscillation ranges up to a metre or even sometimes to two metres. These disturbances may sometimes be due to subterranean movements; but probably they are mainly the effect of atmospheric perturbations, and, in particular, of local storms with a vertical descending movement.[2]

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[1] A. Agassiz, *Amer. Acad.* xii. (1882), p. 108.

[2] F. A. Forel, *Comptes rend.* lxxx. (1875), p. 107, lxxxiii. (1876), p. 712, lxxxvi. (1878), p. 1500, lxxxix. (1879), p. 859; *Assoc. Française*, 1879, p. 493. P. du Bois, *Comptes rend.* cxii. (1891), p. 122. For a valuable monograph on the régime of a typical lake, see Forel's 'Le Léman,' Lausanne, 1892.

The distribution of temperature in lakes is a question of considerable geological interest, in regard to which careful measurements are much needed.

The observations of Sir Robert Christison, at Loch Lomond in Scotland, show that in this sheet of water, which lies 25 feet above sea-level, with a depth of about 600 feet, and is in great measure surrounded with high hills, a tolerably constant temperature of about 42° Fahr. is found to pervade the lowest 100 feet of water.[1] More extended observations have since been made by Dr. John Murray and the staff of the Scottish Marine Station in Lochs Ness, Oich, Morar, and Shiel, as well as in some of the fjords and sounds of the west of Scotland, and the earlier observations have been confirmed. The surface of Loch Morar in September 1887 was found to have a temperature of 57·8° Fahr., but at a depth of 160 fathoms the thermometer had fallen to 42·1°. The surface temperature of Loch Ness in the same month was 54°, but at 120 fathoms 42·1°.[2] Again, in the Lake of Geneva the surface temperature in autumn is 78° Fahr., while the bottom water at a depth of 950 feet was found to mark 41° 7′. The Lago Sabatino near Rome has a temperature of 77° at the surface, but one of 44° at a depth of 490 feet. Similar observations on other deep lakes in Switzerland and Northern Italy indicate the existence in all of them of a permanent mass of cold water at the bottom. The cold heavy water of the surface in winter must sink down, and as the upper layers cannot be heated by the direct rays of the sun, save to a trifling and superficial extent, the temperature of the deep parts of these basins is kept permanently low.

Geological functions.—Among the geological functions discharged by lakes the following may be noticed:

1st. Lakes equalise the temperature of the localities in which they lie, preventing it from falling as much in winter and rising as much in summer as it would otherwise do.[3] The mean annual temperature of the surface water at the outflow of the Lake of Geneva is nearly 4° warmer than that of the air.

2nd. Lakes regulate the drainage of the area below their outfall, thereby preventing or lessening the destructive effects of floods.[4]

3rd. Lakes filter river-water and permit the undisturbed accumulation of new deposits, which in some modern cases may cover thousands of square miles of surface, and may attain a thickness of nearly 3000 feet (Lake Superior has an area of 32,000 square miles; Lago Maggiore is 2800 feet deep). How thoroughly lakes can filter river-water is typically displayed by the contrast between the muddy river which flows in at the head of the Lake of Geneva, and the "blue rushing of the arrowy Rhone," which escapes at the foot. The mouths of small brooks entering lakes afford excellent materials for studying the behaviour of silt-bearing streams when they reach still water. Each rivulet may be observed pushing forward its delta composed of successive sloping layers of sediment (*ante*, p. 397). On a shelving bank, the coarser detritus may repose directly upon the solid rock of the district (Fig. 139).

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[1] For observations on the freezing of this and other lakes, see J. Y. Buchanan, *Nature*, xix. p. 412. On the deep-water temperature of lakes, A. Buchan, *Brit. Assoc.* 1872, Sects. p. 207.

[2] *Proc. Roy. Soc. Edin.* xviii. (1890-91), p. 139.

[3] The lakes of Sweden, which cover one-twelfth of the surface of the country, exercise an important influence on climate according as they are frozen or open. See Prof. Hildebrandsson on the freezing and breaking-up of the ice on the Swedish lakes. *Ann. Bur. Central Météorol. France*, 1878.

[4] Winds, by blowing strongly down the length of a lake, sometimes considerably increase, for the time being, the volume of the outflow. If this takes place coincidently with a heavy rainfall, the flood of the escaping river is greatly augmented. These features are noticed in Loch Tay (D. Stevenson, 'Reclamation of Land,' p. 14). Hence, though on the whole lakes tend to moderate floods in the outflowing rivers, they may, by a combination of circumstances, sometimes increase them.

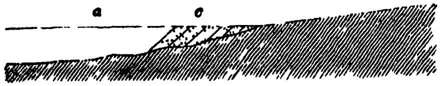

Fig. 139.—Section of a delta-cone pushed by a brook into a lake.

But as it advances into the lake, it may come to rest upon some older lacustrine deposit (Fig. 140). The river Linth since 1860 has annually discharged into Lake Wallenstadt some 62,000 cubic metres of detritus.

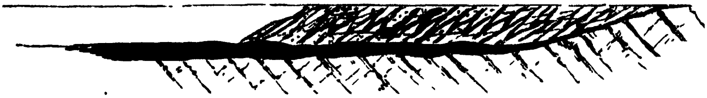

Fig. 140.—Stream-detritus pushed forward over a previous lacustrine silt (*B.*)

A river which flows through a succession of lakes cannot carry much sediment to the sea, unless it has a long course to run after it has passed the lowest lake, and receives one or more muddy tributaries (see p. 397). Let us suppose, for example, that, in a hilly region, a stream passes through a series of lakes (as *a*, *b*, *c*, in Fig. 141). As the highest lake

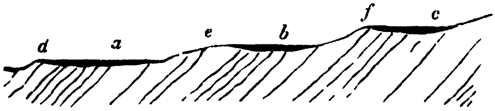

Fig. 141.—Filling up of a succession of lakes (*B.*)

will intercept much, perhaps all, of this sediment, the next in succession will receive little or none until the first is either filled up or has been drained by the cutting of a gorge through the intervening rock at *f*. The same process will be repeated at *e* and *d* until the lakes are effaced, and their places are taken by alluvial meadows. Examples of this sequence of events are of frequent occurrence in Britain.

Besides the detrital accumulations due to the influx of streams, there are some which may properly be regarded as the work of lakes themselves. Even on small sheets of water, the eroding influence of wind-waves may be observed; but on large lakes the wind throws the water into waves which almost rival those of the ocean in size and destructive power. Beaches, sand-dunes, shore-cliffs, and other familiar features of the meeting-line between land and sea, reappear along the margins of such great fresh-water seas as Lake Superior. Beneath the level of the water a terrace or platform is formed, of which the distance from shore and depth vary with the energy of the waves by which it is produced. This platform is well developed in the Lake of Geneva.[1]

Some of the distinctive features of the erosion and deposition that take place in lake-basins have been admirably laid open for study in those basins of vanished lakes which have been so well described by Gilbert, Dutton, Russell, and Upham in the Western Territories of the United States. They have been treated of in a masterly way by Gilbert in his essay on "The Topographic features of Lake-shores."[2]

4th. Lakes serve as basins in which chemical deposits may take place. Of these the most interesting and extensive are those of iron-ore, which chiefly occur in northern latitudes (pp. 146, 483).[3]

5th. Lakes furnish an abode for a lacustrine fauna and flora, receive the remains of the plants and animals washed down from the surrounding country, and entomb these organisms in the growing deposits, so as to preserve a record of the lacustrine and terrestrial life of the period during which they continue. Besides the more familiar pond-snails and fishes, lakes possess a peculiar pelagic fauna, consisting in large measure of entomostracous crustaceans, distinguished more especially by their transparency.[4] These, as well as the organisms of shallower water, doubtless furnish calcareous materials for the mud or marl of the lake bottoms. But it is as receptacles of sediment from the land, and as localities for the preservation of a portion of the terrestrial fauna and flora, that lakes present their chief interest to a geologist. Their deposits consist of alternations of sand, silt, mud, gravel, and occasional irregular seams of vegetable matter, together with layers of calcareous marl formed of lacustrine shells, *Entomostraca*, &c. (p. 484). In lakes receiving much sediment, little or no marl can accumulate during the time when sediment is being deposited. In small, clear, and not very deep lakes, on the other hand, where there is little sediment, or where it only comes occasionally at intervals of flood, thick beds of white marl, formed entirely of organic remains, may gather on the bottom, as has happened in numerous districts of Scotland and Ireland. The fresh-water limestones and clays of some old lake-basins (those of Miocene time in Auvergne and Switzerland, and of Eocene age in Wyoming, for example) cover areas occasionally hundreds of square miles in extent, and attain a thickness of hundreds, sometimes even thousands of feet.

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[1] D. Colladon, *Bull. Soc. Géol. France* (3), iii. p. 661.

[2] *5th Ann. Report U.S. Geol. Survey*, 1885. See also Dutton, in *2nd Report* of same Survey, 1880-81, p. 169 ; I. C. Russell, *3rd Report U.S. Survey*, 1881-82, p. 195 ; *4th Report*, 1882-83, p. 435 ; *8th Report*, 1886-87, p. 201 ; and *Monograph* XI. (1885) of same Survey. W. Upham on the beaches and terraces of a former glacial lake (Lake Agassiz) *Bull. U.S. Geol. Survey*, No. 39 (1887) ; also *8th Ann. Report Geol. and Nat. Hist. Survey Minnesota* (1879), pp. 84-87 ; H. W. Turner on a vanished lake in Mohawk Valley, Plumas County, California, *Bull. Phil. Soc. Washington*, xi. (1891), p. 385.

[3] For an elaborate paper on these lake-ores (See-erze), see Stapff, *Z. Deutsch. Geol. Ges.* xviii. pp. 86-173 ; also A. F. Thoreld, *Geol. Fören. Stockholm. Forh.* iii. p. 20 ; and *postea*, Section iii. p. 483.

[4] F. A. Forel, *Archives d. Sciences*, Sept. 1882. O. E. Imhof, *Ann. Mag. Nat. Hist.* 1884, p. 69.

Existing lakes are of geologically recent origin. Their disappearance is continually in progress by infilling and erosion. Besides the displacement of their water by alluvial accumulations, they are lowered and eventually drained by the cutting down of the barrier at their outlets. Where they are effaced merely by erosion, it must be an excessively slow process, owing to the filtered character of the water (p. 405); but where it is performed by the retrocession of a waterfall at the head of an advancing gorge, it may be relatively rapid after it has once begun.[1] In a river-course it is usual to find a lake-like expansion of alluvial land above each gorge. These plains may be regarded as old lake-bottoms, which have been drained by the cutting out of the ravines (p. 391). Successive terraces often fringe a lake and mark former levels of its waters. It is when we reflect upon the continued operation of the agencies which tend to efface them, that we can best realise why the lakes now extant must necessarily be of comparatively modern date. Their modes of origin are discussed in Book VII.

2. **Saline Lakes**, considered chemically, may be grouped as *salt lakes*, where the chief constituents are sodium and magnesium chlorides with magnesium and calcium sulphates: and *bitter lakes*, which are usually distinguished by their large percentage of sodium carbonate as well as chloride and sulphate (natron-lakes), sometimes by their proportion of borax (borax lakes). From a geological point of view they may be divided into two classes—(1) those which owe their saltness to the evaporation and concentration of water poured into them by their feeders; and (2) those which were originally parts of the ocean.

(*a*) Salt and bitter lakes of terrestrial origin are abundantly scattered over inland areas of drainage in the heart of continents, as in Utah and adjacent territories of North America, and on the great plateau of Central Asia. These sheets of water were doubtless fresh at first, but they have progressively increased in salinity, because, though the water is evaporated, there is no escape for its dissolved salts, which consequently remain in the increasing concentrated liquid. In Ladâkh, extensive lakes formed by the ponding back of valley waters by alluvial fans, have grown saline and bitter, and have become the site of deposits of rock-salt and soda.[2]

The Great Salt Lake of Utah, which has now been so carefully studied by Gilbert and other geologists, may be taken as a typical example of an inland basin, formed by unequal subterranean movement that has intercepted the drainage of a large area, wherein rainfall and evaporation on the whole balance each other, and where the water becomes increasingly salt from evaporation, but is liable to fluctuations in level, according to oscillations of meteorological conditions. The present lake occupies an area of rather more than 2000 square miles, its surface being at a height of 4250 feet above the sea. It is, however, merely the shrunk remnant of a once far more extensive sheet of water, to which the name of Lake Bonneville has been given by Gilbert. It is partly surrounded with mountains, along the sides of which well-defined lines of terrace mark former levels of the water (Fig. 142). The highest of these terraces lies about 940 feet above the present surface of the lake, so that when at its greatest dimensions, this vast sheet of water must have stood at a level of about 5200 feet above the sea, and covered an area of 300 miles from north to south, and 180 miles in extreme width from east to west. It was then certainly fresh, for, having an outlet to the north, it drained into the Pacific Ocean, and in its stratified deposits an abundant lacustrine molluscan fauna has been found.[1] According to Gilbert there are proofs that, previous to the great extension of Lake Bonneville, there was a dry period, during which considerable accumulations of subaerial detritus were formed along the slopes of the mountains. A great meteorological change then took place, and the whole vast basin, not only that termed Lake Bonneville, but a second large basin, Lake Lahontan of King, lying to the west and hardly inferior in area, was gradually filled with fresh water. Again, another meteorological revolution supervened and the climate once more became dry. The waters shrank back, and in so doing, when they had sunk below the level of their outlet, began to grow increasingly saline. The decrease of the water and the increase of salinity were in direct relation to each other until the present degree of concentration has been reached, as shown in the table (p. 411). The Great Salt Lake, at present having an extreme depth of less than 50 feet, is still subject to oscillations of level. When surveyed by the Stansbury Expedition in 1849, its level was 11 feet lower than in 1877, when the Survey of the 40th Parallel examined the ground. From 1866, however, a slow subsidence of the lake has been in progress, consequent upon a diminution of the rainfall. Large tracts of flat land, formerly under water, are being laid bare. As the water recedes from them and they are exposed to the remarkably dry atmosphere of these regions, they soon become crusted with a white saliferous and alkaline deposition, which likewise permeates the dried mud underneath. So strongly saline are the waters of the lake, and so rapid the evaporation, as I found on trial, that one floats in spite of oneself, and the under surfaces of the wooden steps leading into the water at the bathing-places are hung with short stalactites of salt from the evaporation of the drip of the emergent bathers.[2]

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[1] The level of the Lake of Geneva is said to have been lowered about six and a half feet since Roman times (Dausse, *Bull. Soc. Géol. France* (3), iii. p. 140); but this may be explicable by diminution in the water-supply.

[2] F. Drew, 'Jummoo and Kashmir Territories.'

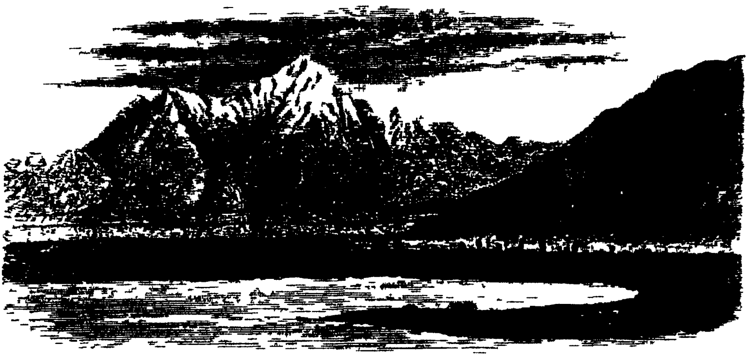

Fig. 142.—Terraces of Great Salt Lake, on the flanks of the Wahsatch Mountains

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[1] For an account of this fauna see R. E. Call, *Bull. U.S. Geol. Surv.* No 11 (1884).

[2] Much information regarding the Great Basin and its lakes is to be found in vol. iii. of Wheeler's *Survey West of 100th Meridian*, vols. i. and iv. of the *Survey of the 40th Parallel*, and *Report of U.S. Geol. Survey*, 1880-81, I. C. Russell, 'Geological History of Lake Lahontan,' *U.S. Geol. Survey Monographs*, No. XI., and in the papers cited *ante*, p. 407.

Some of the smaller lakes in the great arid basin of North America are intensely bitter, and contain large quantities of carbonate and sulphate as well as chloride of sodium. The Big Soda Lake near Ragtown in Nevada contains 129·013 grammes of salts in the litre of water. These salts consist largely of chloride of sodium (55·42 per cent of the whole), sulphate of soda (14·86 per cent), carbonate of soda (12·96 per cent), and chloride of potassium (3·73 per cent). Soda is obtained from this lake for commercial purposes.[1]

(*b*) Salt lakes of oceanic origin are comparatively few in number. In their case, portions of the sea have been isolated by movements of the earth's crust; and these detached areas, exposed to evaporation, which is only partially compensated by inflowing rivers, have shrunk in level, and at the same time have sometimes grown much salter than the parent ocean.

The Caspian Sea, 180,000 square miles in extent, and with a maximum depth of from 2000 to 3000 feet, is a magnificent example. The shells living in its waters are chiefly the same as those of the Black Sea. Banks of them may be traced between the two seas, with salt lakes, marshes, and other evidences to prove that the Caspian was once joined to the Black Sea, and had thus communication with the main ocean. In this case also there are proofs of considerable changes of water-level. At present the surface of the Caspian is 85½ feet below that of the Black Sea. The Sea of Aral, also sensibly salt to the taste, was once probably united with the Caspian, but now rests at a level of 242·7 feet above that sheet of water. The steppes of south-eastern Russia are a vast depression with numerous salt lakes and abundant saline and alkaline deposits. It has been supposed that this depression continued far to the north, and that a great firth, running up between Europe and Asia, stretched completely across what are now the steppes and plains of the Tundras, till it merged into the Arctic Sea. Seals of a species (*Phoca caspica*) which may be only a variety of the common northern form (*Ph. fœtida*), abound in the Caspian, which is the scene of one of the chief seal-fisheries of the world.[2] On the west side of the Ural chain, even at present, by means of canals connecting the rivers Volga and Dwina, vessels can pass from the Caspian into the White Sea.[3]

The cause of the isolation of the Caspian and the other saline basins of that region is to be sought in underground movements which, according to Helmersen, are still in progress, but partly, and, in the case of the smaller basins, probably chiefly in a general diminution of the water-supply all over Central Asia and the neighbouring regions. The rivers that flow from the north towards Lake Balkash, and that once doubtless emptied into it, now lose themselves in the wastes and are evaporated before reaching that sheet of water, which is fed only from the mountains to the south. The channels of the Amur Darya, Syr Darya, and other streams bear witness also to the same general desiccation.[4] At present, the amount of water supplied by rivers to the Caspian Sea appears on the whole to balance that removed by evaporation, though there are slight yearly or seasonal fluctuations. In the Aral basin, however, there can be no doubt that the waters are progressively diminishing, the rate in the ten years between 1848 and 1858 having been 18 inches, or 1·8 inch per annum.

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[1] *Bull. U.S. Geol. Surv.* No. 9 (1884), p. 25. T. M. Chatard, *Amer. Journ. Sci.* xxxvi. (1888), p. 148, and xxxviii. (1889), p. 59.

[2] Another variety or species of seal inhabits Lake Baikal. For an account of the structure and distribution of seals see an interesting monograph by J. A. Allen in *Miscellaneous Publications of U.S. Geological and Geographical Survey of the Territories.* Washington, 1880.

[3] Count von Helmersen, however, has stated his belief that for this extreme northern prolongation of the Aralo-Caspian Sea there is no evidence. The shells, on the presence of which over the Tundras the opinion was chiefly based, are, according to him, all fresh-water species, and there are no marine shells of living species to be met with in the plains at the foot of the Ural Mountains.

[4] *Bull. Acad. Imp. St. Pétersbourg*, xxv. p. 535 (1879). For an account of these rivers and Lake Aral, see H. Wood, *Journ. Roy. Geog. Soc.* xlv. (1875), p. 367, where an estimate is given of the annual amount of evaporation.

Owing to the enormous volume of fresh water poured into it by its rivers, the Caspian Sea is not as a whole so salt as the main ocean, and still less so than the Mediterranean Sea. Nevertheless the inevitable result of evaporation is there manifested. Along the shallow pools which border this sea, a constant deposition of salt is taking place, forming sometimes a pan or layer of rose-coloured crystals on the bottom, or gradually getting dry and covered with drift-sand. This concentration of the water is particularly marked in the great offshoot called the Karaboghaz, which is connected with the middle basin of the Caspian Sea by a channel 150 yards wide and 5 feet deep. Through this narrow mouth there flows from the main sea a constant current, which Von Baer estimated to carry daily into the Karaboghaz 350,000 tons of salt. An appreciable increase of the saltness of that gulf has been noticed; seals, which once frequented it, have forsaken its barren shores. Layers of salt are gathering on the mud at the bottom, where they have formed a salt bed of unknown extent, and the sounding line, when scarcely out of the water, is covered with saline crystals.[1]

The following table shows the proportions of saline ingredients in 1000 parts of the water of some salt lakes:—

Constituents (except where otherwise stated).	Caspian Sea.		In-dertsch Lake (Gobel).	Great Salt Lake, Utah (O. D. Allen).	Elton Lake, Kirghis Steppe (H. Rose).	Dead Sea, from a depth of 185 fathoms.
	Near mouth of R. Ural (Gobel).	At Baku (Abich).				
Chloride of Sodium . .	3·673	8·5267	239·28	118·628	38·3	78·554
,, Magnesium	0·632	0·3039	17·36	14·908	197·5	145·897
,, Calcium .	0·013 ($MgCO_3$)	..	..	..	..	31·075
,, Potassium	0·076	trace	1·01	0·862 (excess Chlorine)	2·3	6·586
Bromide of Magnesium	trace	..	0·05	..		1·374
Sulphate of Calcium .	0·490	1·0742	0·42	0·858	.	0·701
,, Potassium.	0·171 ($CaCO_3$)	0·0554 ($CaCO_3$)	..	5·363	..	
,, Magnesium	1·239	8·2493	8·46	9·321 ($NaSO_4$)	58·2	

Deposits in Salt and Bitter Lakes.—The study of the precipitations which take place on the floors of modern salt lakes is important in throwing light upon the history of a number of chemically-formed rocks. The salts in these waters accumulate until their point of saturation is reached, or until by chemical reactions they are thrown down. The least soluble are naturally the first to appear, the water becoming progressively more and more saline till it reaches a condition like that of the mother-liquor of a salt work. Gypsum begins to be thrown down from sea-water, when 37 per cent of water has been evaporated, but 93 per cent of water must be driven off before chloride of sodium can begin to be deposited. Hence the concentration and evaporation of the water of a salt lake having a composition like that of the sea would give rise first to a layer or sole of gypsum, followed by one of rock-salt. This has been found to be the normal order among the various saliferous formations in the earth's crust. But gypsum may be precipitated without rock-salt, either because the water was diluted before the point of saturation for rock-salt was reached, or because the salt, if deposited, has been subsequently dissolved and removed. In every case where an alternation of layers of gypsum and rock-salt occurs, there must have been repeated renewals of the water-supply, each gypsum zone marking the commencement of a new series of precipitates.

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[1] Von Baer, *Bull. Acad. St. Pétersbourg* (1855-56). See also Carpenter, *Proc. Roy. Geog. Soc.* xviii. No. 4. For the composition of the water of salt and bitter lakes, see the analyses collected by Roth in his 'Chemische Geologie,' i. p. 463 *et seq.*

But from what has now been adduced it is obvious that the composition of many existing saline lakes is strikingly unlike that of the sea in the proportions of the different constituents. Some of them contain carbonate of sodium; in others the chloride of magnesium is enormously in excess of the less soluble chloride of sodium. These variations modify the effects of the evaporation of additional supplies of water now poured into the lakes. The presence of the sodium-carbonate causes the decomposition of lime salts, with the consequent precipitation of calcium-carbonate accompanied with a slight admixture of magnesium-carbonate, while by further addition of the sodium-carbonate a hydrated magnesium-carbonate may be eventually precipitated. Hunt has shown that solutions of bicarbonate of lime decompose sulphate of magnesia with the consequent precipitation of gypsum, and eventually also of hydrated carbonate of magnesia, which, mingling with carbonate of lime, may give rise to dolomite.[1] By such processes the marls or clays deposited on the floors of inland seas and salt lakes may conceivably be impregnated and interstratified with gypseous and dolomitic matter, though in the Trias and other ancient formations which have been formed in enclosed saline waters, the magnesium-chloride has probably been the chief agent in the production of dolomite (*ante*, p. 321).

The Dead Sea, Elton Lake, and other very salt waters of the Aralo-Caspian depression, are interesting examples of salt lakes far advanced in the process of concentration.[2] The great excess of the magnesium-chloride shows, as Bischof pointed out, that the waters of these basins are a kind of mother-liquor, from which most of the sodium-chloride has already been deposited. The greater the proportion of the magnesium-chloride, the less sodium-chloride can be held in solution. Hence, as soon as the waters of the Jordan and other streams enter the Dead Sea, their proportion of sodium-chloride (which in the Jordan water amounts to from ·0525 to ·0603 per cent) is at once precipitated. With it gypsum in crystals goes down, also the carbonate of lime which, though present in the tributary streams, is not found in the waters of the Dead Sea. In spring, the rains bring large quantities of muddy water into this sea. Owing to dilution and diminished evaporation, a check must be given to the deposition of common salt, and a layer of mud is formed over the bottom. As the summer advances and the supply of water and mud decreases, while evaporation increases, the deposition of salt and gypsum begins anew.[3] As the level of the Dead Sea is liable to variations, parts of the bottom are from time to time exposed, and show a surface of bluish-grey clay or marl full of crystals of common salt and gypsum. Beds of similar saliferous and gypsiferous clays, with bands of gypsum, rise along the slopes for some height above the present surface of the water, and mark the deposits left when the Dead Sea covered a larger area than it now does. Save occasional impressions of drifted terrestrial plants, these strata contain no organic remains.[1] Interesting details regarding saliferous deposits of recent origin, on the site of the Bitter Lakes, were obtained during the construction of the Suez Canal. Beds of salt, interleaved with laminæ of clay and gypsum-crystals, were found to form a deposit upwards of 30 feet thick extending along 21 miles in length by about 8 miles in breadth. No fewer than 42 layers of salt, from 3 to 18 centimetres thick, could be counted in a depth of 2·46 metres. A deposit of earthy gypsum and clay was ascertained to have a thickness of 367 feet (112 metres), and another bed of nearly pure crumbling gypsum to be about 230 feet (70 metres) deep.[2]

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[1] Sterry Hunt, in 'Geology of Canada' (1863), p. 575.

[2] The Dead Sea, like the Great Salt Lake, was originally fresh, as proved by shells of *Melania*, &c., found in lacustrine terraces 1300 feet above its present level. Hull, 'Mount Seir,' 1885, pp. 100, 180.

[3] Bischof, 'Chem. Geol.' i. p. 397. Roth, 'Chem. Geol.' i. p. 476.

The desiccated floors of the great saline lakes of Utah and Nevada have revealed some interesting facts in the history of saliferous deposits. The ancient terraces marking former levels of these lakes are cemented by tufa, which appears to have been abundantly formed along the shores where the brooks, on mingling with the lake, immediately parted with their lime. Even at present, oolitic grains of carbonate of lime are to be found in course of formation along the margin of Great Salt Lake, though carbonate of lime has not been detected in the water of the lake, being at once precipitated in the saline solution. The site of the ancient salt lake which has been termed Lake Lahontan displays areas several square miles in extent covered with deposits of calcareous tufa, 20 to 60 and even 150 feet thick. This tufa, however, presents a remarkable peculiarity. It is sometimes almost wholly composed of what have been determined to be calcareous pseudomorphs after gaylussite (a mineral composed of carbonates of calcium and sodium with water)—the sodium of the mineral having been replaced by calcium. When this variety of tufa, distinguished by the name of *thinolite*, was originally formed, the waters of the vast lake must have been bitter, like those of the little soda-lakes which now lie on its site—a dense solution in which carbonate of soda predominated. On the margin of one of the present Soda Lakes, crystals of gaylussite now form in the drier season of the year. Yet no trace of carbonate of lime has been detected in the water. The carbonate of lime in the crystals must be derived from water which on entering the saline lakes is at once deprived of its lime.[3]

§ 5. Terrestrial Ice.

Fresh water, under ordinary circumstances, when it reaches a temperature of 32° Fahr. passes into the solid state by crystallizing into ice. In this condition, it performs a series of important geological operations before being again melted and relegated to the general mass of liquid terrestrial waters. Five conditions under which ice occurs on the land deserve notice, viz., frost, frozen rivers and lakes, hail, snow, and glaciers.

Frost.—Water, if perfectly still, may fall below the freezing-point without freezing, but when it is then moved, it at once freezes over. In freezing, water expands. If it be confined in such a way that expansion is impossible, it remains liquid even at temperatures below the freezing-point; but the instant that the pressure is removed this chilled water becomes ice. There is a constant effort on the part of the water to expand and become solid, very considerable pressure being needed to counterbalance this expansive power, which increases as the temperature sinks. At 30° Fahr. the pressure must amount to 146 atmospheres, or the weight of a column of ice a mile high, or 138 tons on the square foot. Consequently when the water freezes at a lower temperature, its pressure on the walls of its enclosing cavity must exceed 138 tons on the square foot. Bombshells and cannon filled with water and hermetically sealed have been burst in strong frosts by the expansion of the freezing water within them. In nature, the enormous pressures which can be obtained artificially occur rarely or not at all, because the spaces into which water penetrates can hardly ever be so securely closed as to permit the water to be cooled down considerably below 32° Fahr. before freezing. But ice forming in cavities at even two or three degrees below the freezing-point exerts an enormous disruptive force.

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[1] Lartet, *Bull. Soc. Géol. France* (2), xxii. p. 450 *et seq.* Below the high terraces, containing lacustrine shells, evidence of shrinkage and concentration is supplied by gypseous marls and a bed of salt (30 to 50 feet), 600 feet above the present water-level.

[2] Lesseps, *Comptes rend.* lxxviii. p. 1740, *Ann. Chim. et Phys.* (5), iii. p. 139. Bader, *Verh. Geol. Reichsanst.* 1869, p. 288.

[3] King, *Exploration of the* 40*th Parallel*, i. p. 510. See also on the crystallographic form and chemical composition of the thinolite and its original mineral, E. S Dana, *Bull. U.S. Geol. Surv.* No. 12 (1884).

Soils and rocks, being all porous, and usually containing a good deal of moisture, have their particles pushed asunder by the freezing of this interstitial water. Stones, stumps of trees, or other objects imbedded in the ground, are squeezed out of it. When a thaw comes, the soil seems as if it had been ground down in a mortar. Water, freezing in the innumerable joints and fissures of rocks, exerts great pressure upon the walls between which it lies, pushing them asunder as if a wedge were driven between them. When this ice melts, the separated masses do not return to their original position. Their centre of gravity in successive winters becomes more and more displaced, until the sundered masses fall apart. In mountainous districts, where the winters are severe, and in high latitudes, much waste is thus produced on exposed cliffs and loose blocks of rock. Some measure of its magnitude may be seen in the heaps of angular rubbish which in these regions so frequently lie at the foot of crags and steep slopes. At Spitzbergen and on the coast of Greenland, the observed amount of destruction caused by frost is enormous. The short warm summer, melting the snow, fills the pores and joints of the rocks with water, which when it freezes splits off large blocks, launching them to the base of the declivities, where they are further broken up by the same cause. In some countries, where the winters are severe, the soil-cap has been observed to be pushed or to creep downhill from the action of frost.[1]

Frozen Rivers and Lakes.—In countries such as Canada, the lakes and rivers are frozen over in winter with a cake of ice 1½ to 2½ feet thick. This cake as it forms expands and presses against the shores. A continuance of frost leads to a contraction of the ice already formed and to the consequent opening of vertical fissures, into which the water from below ascends and freezes. When a subsequent rise in temperature causes an expansion of the superficial crust; the ice once more presses against the shores. When these are steep the ice yields and either breaks up along its margin or assumes an undulating surface over the lake; but where they are sloping it is pushed up the slope, carrying with it earth and boulders. Similar results are repeated during subsequent rises and falls of temperature, the débris being driven further up the shore, until it sometimes accumulates in a mound or wall along the outer edge of the broken ice. When the ice melts this embankment of displaced material is left as a memorial of the severity of the climate. Such "shore-walls" are of common occurrence on the margins of many lakes in Canada and the United States.[1] Under certain conditions, also, what is called "anchor-ice" forms on the bottoms of the rivers and rises to the surface.[2] In several ways, geological changes are thus effected. Mud, gravel, and boulders encased in the anchor-ice or pushed along by it on the bottom, are moved from their position. This ice, formed in considerable quantity in the rapids of the Canadian rivers, is carried down stream and accumulates against the bars and banks, or is pushed over upon the surface of the upper ice. By its accumulation a temporary barrier is formed, the bursting of which causes destructive floods. When the ice breaks up in early summer, cakes of it which have been formed along shore, and have enclosed beach-pebbles and boulders, float off so as either to drop these in deeper water or to strand them on some other part of the shore.

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[1] Kerr, *Amer. Journ. Sci.* xxi. (1881), p. 345; C. Davidson, *Geol. Mag.* 1889, p. 255.

This kind of transport takes place on a great scale on the St. Lawrence. The islets of boulder-clay and solid rock are fringed with blocks which have been stranded by ice and which are ready to be again enclosed, and floated off further down stream. Should a gale arise during the breaking up of the frost, vast piles of ice, with mingled gravel and boulders, may be driven ashore and pushed up the beach; even blocks of stone of considerable size are sometimes forced to a height of several yards, tearing up the soil on their way, and helping to form a bank above the water-level. In the same river, great destruction of banks has been caused by rafts of ice, and particularly of anchor-ice. Crab Island, for example, which was about an acre and a half in extent at the beginning of this century, has entirely disappeared, its place being indicated merely by a strong ripple of the water, which is every year getting deeper over the site.[3] Other islands have also been destroyed. Great damage is frequently done to quays and bridges in the same region, by masses of river-ice driven against them on the arrival of spring. Reference has already been made to the increased power of transport and erosion acquired by frozen rivers, and especially when, as in Siberia, their ice breaks up in the higher parts of their courses, before it gives way in the lower (p. 382).

Hail, the formation of which is not yet well understood,[4] falls chiefly in summer and during thunderstorms. When the pellets of ice are frozen together so as to reach the ground in lumps as large as a pigeon's egg, or larger, great damage is often done to cattle, flying birds, and vegetation. Trees have their leaves and fruit torn off, and farm crops are beaten down.

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[1] C. A. White, *Amer. Naturalist*, ii. (1868), p. 148; G. K. Gilbert, *5th Ann. Rep. U. S. Geol. Survey*, 1885, p. 109.

[2] These conditions, according to Dr. Rae (*Nature*, xxi. p. 538), are: 1st, a rocky or stony bottom; 2nd, shallow water as compared with that higher up the stream; 3rd, a swifter current and rougher water, in comparison with a smooth and slower motion immediately above. It is a loose, slushy, adhesive kind of ice. See also *Nature*, xxi. p. 612; xxii. 31, 54.

[3] Bleasdell, *Q. J. Geol. Soc.* xxvi. p. 669; xxviii. p. 292.

[4] For an account of the different theories proposed to account for hail, see Prof. Viguier, *Assoc. Française*, 1879, p, 543; 1880, p. 436.

Snow.—In those parts of the earth's surface where, either from geographical position or from elevation into the upper cold regions of the atmosphere, the mean annual temperature is below the freezing-point, the condensed moisture falls chiefly as snow, and remains in great measure unmelted throughout the year. A line, termed the *snow-line*, can be traced, below which the snow disappears in summer, but above which it continues to cover the whole or great part of the surface. The snow-line comes down to the sea around the poles. Between these limits it rises gradually in level till it reaches its highest elevation in tropical latitudes. South of lat. 78° N. it begins to retire from the sea-level, so that on the coast of northern Scandinavia it is already nearly 3000 feet above the sea. None of the British mountains quite reach it. In the Alps it stands at 8500 feet, on the Andes at 18,000 feet, and on the northern slopes of the Himalayas at 19,000 feet.

Snow exhibits two different kinds of geological behaviour: (1) conservative, and (2) destructive. (1) Lying stationary and unmelted, it exercises a protective influence on the face of the land, shielding rocks, soils, and vegetation from the effects of frost. On low grounds this is doubtless its chief function. (2) *a*. When snow falls in a partially melted state it is apt to accumulate on branches and leaves, until by its weight it breaks them off, or even bears down entire trees. Great destruction is thus caused in dense forests. *b*. Snow accumulating on gentle slopes and slowly sliding downwards, pushes soil or loose stones down-hill. Considerable transport of rotted rock and boulders may thus arise.[1] *c*. Snow on steep mountain slopes is frequently during spring and summer detached in sheets from 10 to more than 50 feet thick and several hundred yards broad and long, which rush down as *avalanches* (Lawinen), sweep away trees, soil, or rocks, and heap them up in the valleys.[2] Besides the destruction caused by the avalanche itself, sometimes much damage arises from the sudden violent wind to which it gives rise.[3] *d*. Another indirect effect of snow is seen in the sudden rise of rivers when warm weather rapidly melts the mountain snows. Many summer freshets are thus caused in Switzerland. It is to the melting of the snows, rather than to rain, that rivers descending from snowy mountains owe their periodical floods. Hence such rivers attain their greatest volume in summer. *e*. A curious destructive action of snow has been observed

[1] H. Y. Hind, *Canadian Naturalist*, viii. (1878), pp. 967, 976.

[2] An avalanche near Ormons Dessus, Canton Vaud (Dec. 1882), piled up a mass of ice and snow 200 feet thick (some of the ice-blocks being 18 feet long), and covered 3 square km. of ground. *Nature*, xxvii. p. 181. Streams may be thus blocked up, as the Inn was at Süs in 1827. For accounts of avalanches, see J. Coaz, 'Die Lawinen in den Schweizeralpen,' Berne, 1881.

[3] *Geol. Mag.* 1888 p. 155.

on the sides of the Rocky Mountains, where the drifting of snow-crystals by the wind in some of the passes has damaged and even killed the pine-trees, wearing away the foliage, cutting off the bark, and even sawing into the wood for several inches.[1]

Glaciers[2] **and Ice-sheets.**—Glaciers are rivers of ice formed by the slow movement and compression of the snow, which, by gravitation, creeps downward into valleys descending from snow-fields. The snow in the higher regions is loose and granular. As it moves downward it becomes firmer, passing into the condition of *névé* or *firn* (p. 148). Gradually, as the separate granules are pressed together and the air is squeezed out, the mass assumes the character of blue compact crystalline ice. From a geological point of view, a glacier may be regarded as the drainage of the snowfall above the snow-line, as a river is the drainage of the rainfall. A glacier, like a river, is always in motion, though so slowly that it seems to be solid and stationary. It descends as a brittle, thick-flowing substance, like pitch or resin. The motion is unequal in the different parts, the centre moving faster than the sides and bottom, as was first ascertained through accurate measurement by J. D. Forbes, who found that in the Mer de Glace of Chamouni, the mean daily rate of motion in the summer and autumn was from 20 to 27 inches in the centre, and from 13 to 19½ near the side. Helland has observed that on the west coast of Greenland the glacier of Jacobshavn has a remarkably rapid motion, its rate for twenty-four hours ranging from 48·2 feet to 64·8 feet. The ice of the fjord of Torsukatak, nearly five miles wide, moves with a mean rate of 24 feet in a day; that of Karajak, four and a half miles broad, moves 30 feet daily. G. F. Wright, from observations made by him in Alaska, inferred that the Muir glacier there, enters a sea-inlet at an average rate of forty feet per day (70 feet in the centre and 10 feet near the margin) in the month of August;[3] but a more recent measurement by Dr. Reid in the summer of 1890 gives a maximum rate of only seven feet in a day.

The consequence of this differential motion is seen in the internal banded structure of a glacier, in the downward curvature of the transverse fissures (crevasses), and in the arrangement of the lines of rubbish thrown down at the termination, which often present a horse-shoe shape, corresponding to that of the end of the ice by which they were discharged.[4]

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[1] Clarence King, *Exploration of 40th Parallel*, i. p. 527.

[2] On glaciers and their geological work, see De Saussure, 'Voyages dans les Alpes,' § 535; Agassiz, 'Études sur les Glaciers,' 1840; Rendu, 'Théorie des Glaciers de la Savoie,' *Mem. Acad. Savoie*, x., translated into English, 1875; J. D. Forbes, 'Travels in the Alps,' 1843, 'Norway and its Glaciers,' 1853; 'Occasional Papers on Glaciers,' 1859; Tyndall, 'Glaciers of the Alps,' 1857; Mousson, 'Gletscher der Jetztzeit,' 1854; A. Heim, 'Handbuch der Gletscherkunde,' Stuttgart, 1885; E. Richter, 'Gletscher der Ostalpen,' Stuttgart, 1888.

[3] *Amer. Journ. Sci.* xxxiii. (1887), p. 10. For the glaciers of the United States see Wright's 'Ice-Age in America'; H. P. Cushing, *American Geologist*, 1891, p. 207; Hayes, *National Geographic Magazine*, iv. (1892), p. 150; Russell, *Amer. Journ. Sci.* xliii. (1892), p. 169. *5th. Ann. Rep. U. S. Geol. Surv.* (1885).

[4] The cause of glacier motion has been a much-vexed question in physics. See, besides

Under the term Ice-sheet is included the deep mantle of snow and ice which, in the Polar regions, covers the land and creeps out to sea. In high Arctic, and still more in Antarctic latitudes, land-ice, formed from the drainage of a great snow-field, attains its greatest dimensions. The land in these regions is buried under an ice-cap which ranges up to a thickness (in the South Polar circle) of 10,000 feet (2 miles) or even more. Greenland lies under such a pall of snow that all its inequalities, save only the steep mountain-crests and peaks near the coast, are concealed. The snow, creeping down the slopes, and mounting over the minor hills, passes beneath by pressure into compact ice. From the main valleys great glaciers, like vast tongues of ice, 2000 or 3000 feet thick, and sometimes 50 miles or more in breadth, push out to sea, where they break off in huge fragments that float away as icebergs.[1] As far back as 1777, Captain Cook gave interesting descriptions of the glaciers of South Georgia (Lat. 54° S.), which reach the sea in a line of cliffs (Fig. 149).

Glaciers, though naturally most abundantly developed in arctic and antarctic regions, may be met with in any latitude wherever a sufficiently extensive area of snow accumulates and remains permanent throughout the year. They occur even in equatorial regions where the ground rises sufficiently high above the snow-line. They are found in great force among the Himalaya mountains, while among the Andes of Quito, close to the equator, many glaciers have been noted; the great mountain of Chimborazo (20,498 feet), for example, being capped with ice and sending glaciers out in all directions.[2] Hence the peculiar geological results effected by glacier-ice are not restricted to definite latitudes, but may be encountered, under the necessary limitations, from the equator to the poles.

Some features of geological importance in the behaviour of a glacier as it descends its valley deserve mention here. When the ice has to travel over a very uneven floor, some portions may get embayed, while overlying parts slide over them. A massive ice-sheet may thus have

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the works cited in the foregoing note, J. Thomson, *Proc. Roy. Soc.* 1856-7; Mosely, *op cit.* 1869; Croll, 'Climate and Time,' 1875; Hopkins, *Phil. Mag.* 1845; *Phil. Trans.* 1862; Helmholtz, *Heidelberg Verhandl. Nat. Med.* 1865, p. 194; *Phil. Mag.* 1866, p. 22; Pfaff, *Akad. Bayer.* 1876. A valuable history of the controversy regarding glacier motion has been prepared by Sir H. H. Howorth, *Mem. Proc. Manchester Lit. Phil. Soc.* iv. (1891). The conclusion to which the most recent researches point coincides essentially with that enunciated upwards of 40 years ago by J. D. Forbes, that the motion of a glacier "is that of a slightly viscous mass, partly sliding upon its bed, partly shearing upon itself under the influence of gravity." Trotter, *Proc. Roy. Soc.* xxxviii. p. 107. The banded structure of glacier-ice may be compared with shear-structure (pp. 316, 544).

[1] The Greenland snow-fields and glaciers are well described in the "Meddelelser om Grönland"—the detailed report of a Danish commission appointed to investigate that country. The first volume was published in 1879, and ten have subsequently appeared. See also Nordenskiöld, *Geol. Mag.* 1872, Marr, *Geol. Mag.* 1887, p. 151. H. Rink, *Edin. Geol. Soc.* v. (1887), p. 286. E. von Drygalski, *Zeitsch. Gesell. f. Erdkunde*, Berlin (1892). See also Nansen, *Petern. Mittheil.* Erganzungsheft, No. 105 (1892).

[2] On glaciers of Ecuador see Whymper, 'Travels Amongst the Great Andes,' p. 348.

many local eddies in its lower portions, the ice there even travelling for various distances, according to the nature of the ground, obliquely to the general flow of the main mass, as is remarkably displayed in the Greenland ice where it flows round the isolated rocks or "Nunatakker" which rise out of it. It there acquires in some places a remarkably beautiful banded structure, which in lenticular banding and folding presents a close resemblance to the characteristic banded and plicated structure of many ancient gneisses.[1] In descending by a steep slope to a more level part of its course, a glacier becomes a mass of fissured ice in great confusion. It descends by a slowly creeping ice-fall, where a river would shoot over in a rushing waterfall. A little below the fall the fractured ice, with all its chaos of pinnacles, bastions, and chasms, is pressed together again, and by regelation becomes once more a solid mass (Fig. 143).

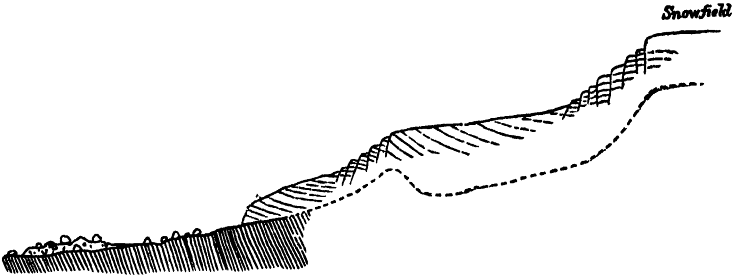

Fig. 143.—Section of Glacier with Ice-falls, Fondalen, Holands Fjord, Arctic Norway.

The body of the glacier throughout its length is traversed by a set of fissures called *crevasses*, which, though at first as close-fitting as cracks in a sheet of glass, widen by degrees as the glacier moves on, till they form wide yawning chasms, reaching, it may be, to the bottom of the ice, and travelling down with the glacier, but apt to be effaced by the pressing of their walls together again as the glacier winds down its valley. The glacier continues to descend until it reaches that point where its rate of advance is just equalled by its liquefaction. There it ends, its place down the rest of the valley being taken by the tumultuous river of muddy water which escapes from under the melting extremity of the ice. A prolonged augmentation of the snowfall will send the foot of the glacier further down the valley; a diminution of the snowfall or a general rise of temperature will cause it to retreat further up.

Considerable variations in the thickness and length of glaciers have been observed within the last two or three generations, due to oscillations of temperature and wetness. Thus the glacier of La Brenva, on the Italian side of Mont Blanc, shrank to such an extent in the twenty-four years succeeding 1818, that its surface at one place was found to have subsided no less than 300 feet.[2] The glaciers of Mont Blanc had ceased to advance about 1854, and in twelve years, from 1854 to 1865, the Glacier des Bossons had receded 332 metres, that of Bois 188 metres, that of Argentière 181 metres, and that of Tour 520 metres. Similar facts have been observed in the Bernese Oberland and the Tyrol, but with some local exceptions, in particular the Gorner and Aar glaciers.[1] At the Pasterzen glacier, which shrank back about 6 or 8 metres annually, the retreat was changed in 1883 into a forward movement, possibly indicating that the minimum had been reached and that a new advance of the ice had begun.[2] Since 1855 the glaciers of the Pyrenees and Caucasus have also shrunk.[3] The glaciers of Greenland and Alaska were formerly much larger than they are now. The Muir glacier in Alaska is said to have retreated half a mile in four years preceding 1890.[4]

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[1] See by way of illustration plates ix.-xii. of a paper on the glaciers and inland ice of Greenland by E. von Drygalski, *Zeitsch. Gesell. f. Erdkunde*, Berlin (1892).

[2] J. D. Forbes, 'Travels in the Alps,' p. 205.

In a mountainous region such as the Alps, or a table-land like Scandinavia, where a considerable mass of ground lies above the snow-line, three varieties of glaciers may be observed.

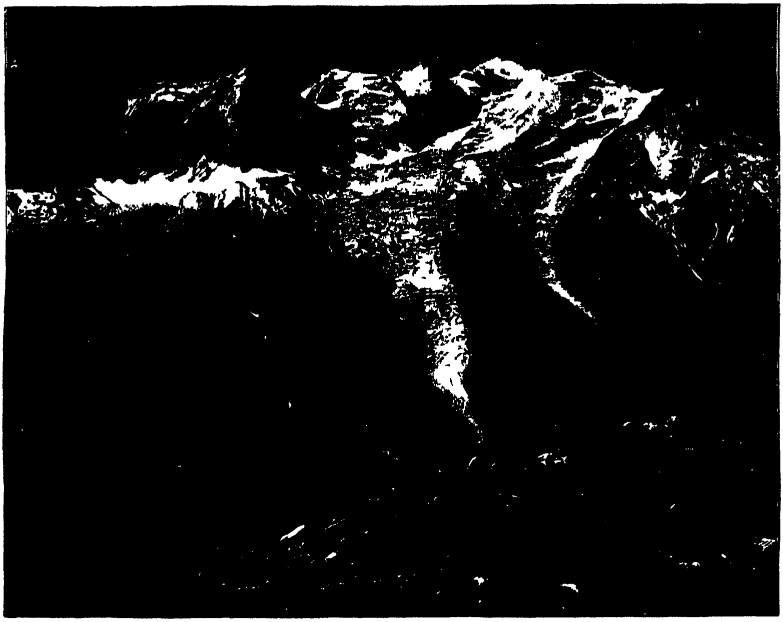

Fig. 144.—Snow-Fields and Glaciers of Mont Blanc, seen from the top of Mount Brevent.

(1) Glaciers of the first order (valley-glaciers) come down well below the snow, and extend into the valleys. In high latitudes they reach the sea. The Humboldt Glacier in North Greenland presents a wall of ice 60 miles long and rising 300 feet above the sea, which washes the base of the cliff. The spiry peaks and sharp crests of the Alps rise through the snow, which they thus isolate into distinct basins (Firnmulden), averaging perhaps two square miles in area, whence glaciers proceed. The number

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[1] L. Gruner, *Comptes rend.* lxxxii. p. 632. *Bull. Soc. Géol. Fran.* iv. (3e sér.) On periodic variations of Alpine Glaciers, see Forel, *Arch. Sci. Bib. Univ.* Geneva, July 1881.

[2] F. Seeland, *Zeitsch Deutsch-Oesterr. Alpenvereins*, 1884, p. 51.

[3] Ch. Dufour, *Assoc. Française*, 1880, p. 449. The Norwegian glaciers are now retreating.

[4] H. P. Cushing, *American Geologist*, 1891, p. 215.

of glaciers among the Alps has been estimated at 2000, covering a total area of from 3000 to 4000 square kilometres (Figs. 144, 145). They average perhaps from 3 to 5 miles in length The Great Aletsch Glacier is nearly 10 (or, including the snow-field, nearly 15) miles long, with a mean breadth of 5900 feet, and descending to 4439 feet above the sea. The thickness of the ice in the Alpine glaciers must often be as much as 800 to 1200 feet. It has been computed that the Gorner Glacier is large enough to make three cities as big as London. The great snow-fields of Arctic Norway accumulate on broad table-lands, from which they send glaciers down into the valleys (Figs. 143, 146).

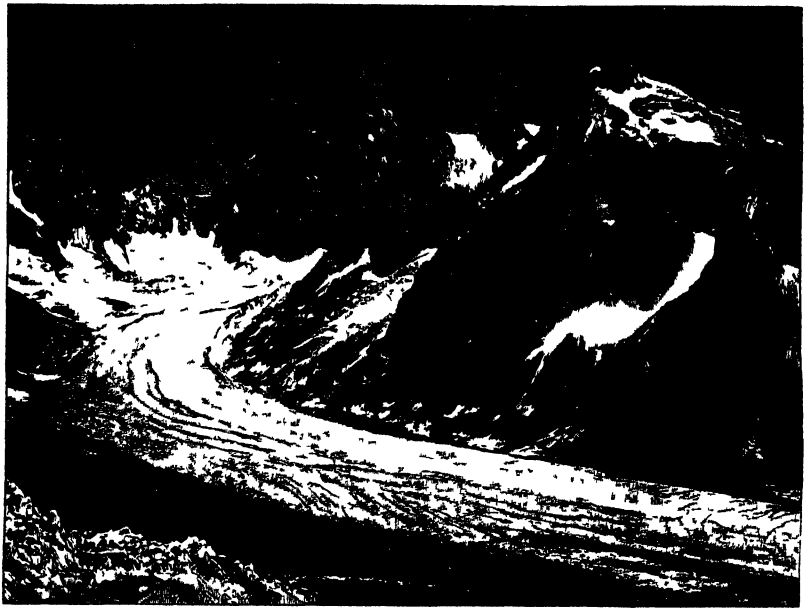

Fig 145—Glacier de Lechaud, with the Grandes Jorasses and Aiguille de Tacul

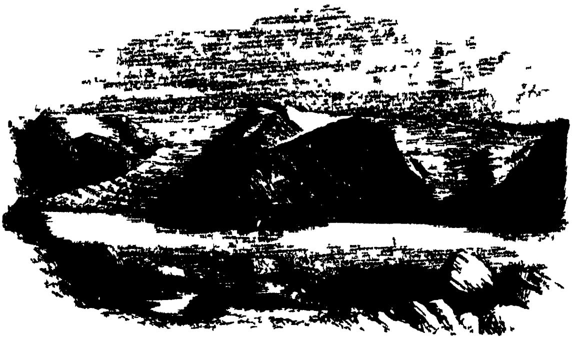

Fig 146—View of the two Glaciers of Fondalen, Holands Fjord, Arctic Norway

(2) Glaciers of the second order (Corrie-glaciers, Hängegletscher) hardly creep beyond the high recesses wherein they are formed, and do not therefore reach as far as the nearest valley. Many beautiful examples of this type may be seen along the steep declivities which intervene between the snow-covered plateau of Arctic Norway and the sea.

(3) Re-cemented Glaciers (*Glaciers remaniés*).—These consist of fragments which, falling from an ice-cliff crowning precipices of rock, are re-frozen at the bottom into a solid mass that creeps downward as a glacier usually of the second order. Probably the best illustrations in Europe are furnished by the Nus Fjord, and other parts of the north of Norway. In some cases a cliff of "firn" resting on blue ice appears at the top of the precipice—the edge of the great "sneefond," or snow-field—while several hundred feet below, in the corrie or cwm at the bottom, lies the re-cemented glacier, white at its upper edge, but acquiring somewhat of the characteristic blue gleam of compact ice as it moves towards its lower margin. A beautiful example of this kind was visited by me at the head of the Jökuls Fjord in Arctic Norway in 1865. When making the sketch from which Fig. 147 is taken, I observed that the ice from the edge of the snow-field above slipped off in occasional avalanches, which sent a roar as of thunder down the valley, while from the shattered ice, as it rushed down the precipices, clouds of white snow-dust rose into the air. The débris thus launched

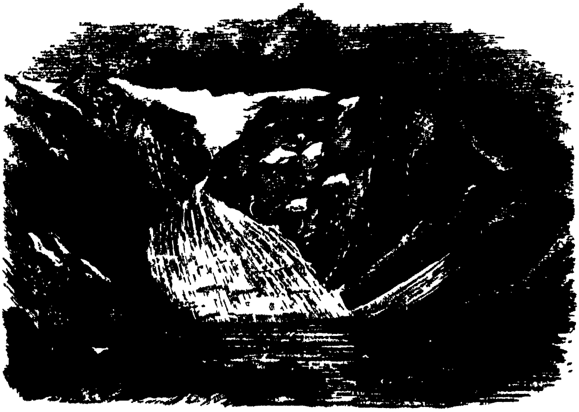

Fig. 147.—View of re-cemented Glacier, Jokuls Fjord, Arctic Norway.

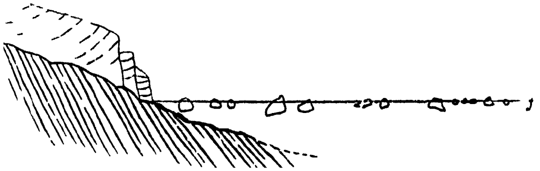

Fig. 148.—Section showing the production of Icebergs at the foot of the Jokuls Fjord Glacier.

into the defile beneath accumulates there by mutual pressure into a tolerably solid mass, which moves downward as a glacier, and actually reaches the sea-level—the only example, so far as I am aware, of a glacier on the continent of Europe which attains so low an altitude. As it descends it is crevassed, and when it comes to the edge of the fjord, slices from time to time slip off into the water, where they form fleets of miniature icebergs, with which the surface of the fjord (*f* in Fig. 148) is covered.

Great destruction is sometimes caused by the breaking off of the end of glaciers which terminate on steep ground. The sudden dislocation of the ice and its reduction to fragments, and even to powder, causes a considerable proportion of it to melt. A mingled mass of ice and water is thus discharged, which, meeting with loose moraine stuff, may speedily become a moving debacle of mud. Such, according to M. Forel, was the origin of the destructive avalanche which on 12th July 1892 swept away some thirty houses and killed about 150 people, in the valley of Montjoie, which joins that of the Arve, not far below Chamouni.[1]

Another incidental effect of the movement of glaciers is to be seen when the ice, barring the mouth of a tributary valley, dams back the streams flowing therein, and causes a lake to form. This result may be observed at the Märjelen See, on the great Aletsch Glacier, and elsewhere on the Alpine chain. If this arrest of the water is temporary, great damage may be done by the bursting of the ice-dam and the consequent sudden rush of the liberated water. If, on the other hand, the glacier is massive enough to form a permanent barrier, the water may rise behind it so as to fill the tributary valley, and even escape by a pass at its head. Successive diminutions of the mass of ice will lead to corresponding lowerings of the level of the lake, each prolonged rest of the water at one level being marked by a shelf or terrace formed as a beach-line along the shore. The famous "parallel roads" of Glen Roy are a striking illustration of this kind of geological history. (Book VI. Part V. Sect. i. § 1.)

Work done by Glaciers.—Glaciers have two important geological tasks to perform—(1) to carry the débris of the mountains down to lower levels; and (2) to erode their beds.

(*a*) *Transport.*—This takes place chiefly on the surface of the ice. Descending its valley, the glacier receives and bears along on its margin the earth, stones, and rubbish which, loosened by frost, or washed down by rain and rills, slip from the cliffs and slopes. In this part of its work, the glacier resembles a river which carries down branches and leaves from the woods on its banks. Most of the detritus rests on the surface of the ice. It includes huge masses of rock, sometimes as big as a large cottage, all which, though seemingly at rest, are slowly travelling down the valley with the ice, liable at any moment to slip into the crevasses which may open below them. When they thus disappear, they may descend to the bottom of the ice, and move with it along the rocky floor, which is no doubt the fate of a large proportion of the smaller stones and sand. But the large stones seem, sometimes at least, to be cast up again by the ice to the surface of the glacier at a lower part of its course. Whether therefore on the ice, in the ice, or under the ice, a vast quantity of detritus is continually travelling with the glacier down towards the plains. The rubbish lying on the surface is called *moraine* stuff. Naturally it accumulates on either side of the glacier, where it forms the so-called *lateral moraines*. When two glaciers unite, their two adjacent lateral moraines are brought together, and travel thereafter down the centre of the glacier as a *medial moraine*. In Fig. 150 the left lateral moraine (3) of glacier B unites with the right lateral moraine (2) of A to form the medial moraine *b*, while the other moraines (1, 4) continue their course and become respectively the right and left lateral moraines (*c*, *a*) of the united glacier. A glacier formed by the union of many tributaries in its upper parts, may have numerous medial lines of moraine, so many indeed as sometimes to be covered with débris,

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[1] *Comptes rend.* cxv. (1892), p. 193. Other writers assign the bursting of a glacier-lake as the cause.

Fig. 149.—View of Glacier in Possession Bay, South Georgia.

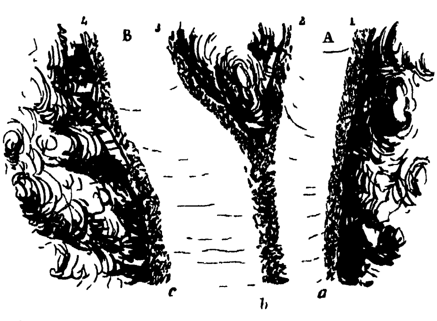

Fig. 150.—Map of the union of two glaciers, showing junction of two lateral into one medial Moraine.

to the complete concealment of the ice. At such parts the glacier appears to be a bare field or earthy plain, rather than a solid mass of clear ice of which only the surface is dirty with rubbish. At the end of the glacier, the pile of loose materials is tumbled upon the valley in what is called the *terminal moraine*.

Beneath the ice of the Swiss glaciers lies a thin inconstant layer of fine wet mud, sand, and stones, derived partly from the descent of materials from the surface down the crevasses, partly from the rocks of the sides and bottom of the glacier-bed. These materials may be seen fixed sometimes in the ice itself. Though it may locally accumulate, this layer is apt to be removed by the ice or by the water that flows under the glacier. It is known to Swiss geologists as the *moraine profonde* or *Grundmoranc* (= boulder clay, till or bottom-moraine). The sheet of ice that once filled the broad central plain of Switzerland, between the Alps and the Jura, certainly pushed a vast deal of mud, sand, and stones over the floor of the valley, and this material has been left as a covering, like the till of Northern Europe.[1]

When from any cause a glacier diminishes in size, it may drop its blocks upon the sides of its valley, and leave them there, sometimes in the most threatening positions. Such stranded stones are known as *perched blocks*. Those of each valley belong to the rocks of that valley; and if there be any difference between the rocks on the two sides, the perched blocks, carried far down from their sources, still point to that difference, for they remain on their own original side. But during a former great extension of the glaciers of the northern hemisphere, blocks of rock have been carried out of their native valleys, across plains, valleys, and even considerable ranges of hills.

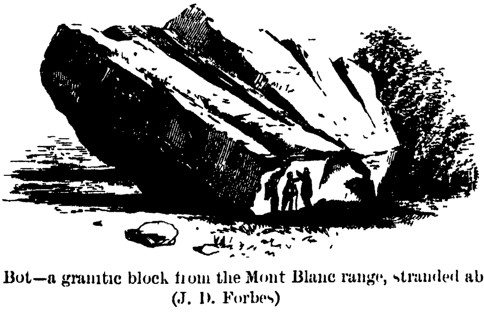

Fig. 151.—Pierre a Bot—a granitic block from the Mont Blanc range, stranded above Neufchatel (J. D. Forbes)

Such "erratics" (Findlinge) not only abound in the Swiss valleys, but cross the great plain of Switzerland, and appear in numbers high upon the flanks of the Jura. Since the latter mountains consist chiefly of limestone, and the blocks are of various crystalline rocks belonging to the higher parts of the Alps, the proof of transport is irrefragable. Thousands of them form a great belt of boulders extending for miles at an average height of 800 feet above the Lake of Neufchâtel (Fig. 151). These consist of the protogine granite of the Mont Blanc group of mountains, and must have travelled at least 60 or 70 miles. One of the most noted of them, the Pierre à Bot (toad-stone), which lies about two miles west of Neufchâtel, measures 50 (French) feet in length by 20 in width, and 40 in height. It is estimated to contain 40,000 cubic feet, and to weigh about 3000 tons.[1] The celebrated "blocks of Monthey" consist of huge masses of granite, disposed in a belt, which extends for miles along the mountain slopes on the left bank of the Rhone, near its union with the Lake of Geneva. On the southern side of the Alps, similar evidence of the transport of blocks from the central mountains is to be found. On the flanks of the limestone heights on the farther side of the Lake of Como, blocks of granite, gneiss, and other crystalline rocks lie scattered about in hundreds (Fig. 152).

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[1] In 1869 I examined a characteristic section of an ancient *moraine profonde* near Solothurn, full of scratched stones, and lying on the striated pavement of rock to be immediately described as further characteristic of ice-action. It closely resembled the boulder-clay of Northern Europe.

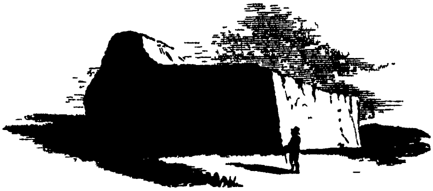

Fig. 152.– Angular erratic block on the north side of the Alpi di Pravolta, Lake of Como (B.).

Before the numerous facts had been collected and understood which prove a former great augmentation in the size of the Alpine glaciers, it was believed by many geologists that the erratics stranded along the flanks of the Jura mountains had been transported on floating ice, and that Central Europe was then in great part submerged beneath an icy sea. It is now universally admitted, however, that the transport has been entirely the work of glaciers. Instead of being confined, as at present, to the higher parts of their valleys, the glaciers extended down into the plains. As already stated, they filled the great depression between the Oberland and the Jura, and, rising high upon the flanks of the latter chain, actually overrode some of its ridges. Similar evidence in the hilly parts of Britain, as well as in other parts of Europe and America, no longer the abode of glaciers, shows that a great extension of snow and ice at a recent geological period prevailed in the northern hemisphere, as will be described in the account of the Glacial Period in Book VI. Extensive as are the present ice-sheets and glaciers of Greenland, they are undoubtedly much reduced from their former size, for bare ice-worn rocks are found beyond their limits, as in Scandinavia.[2]

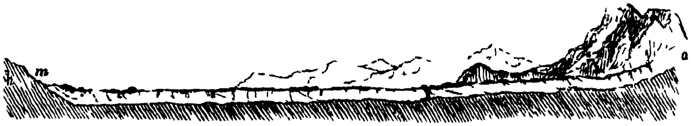

Fig. 153.—Section to show the extension of the Alpine Glaciers (a) across the Plain of Switzerland, and the transport of blocks to the sides of the Jura (m) (B.)

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[1] Forbes, 'Travels in the Alps,' p. 49.

[2] Meddelelser om Grönland. H. Rink, *Petermann's Mittheilungen*, 1884, p. 136, gives some recent results of Greenland exploration. Much useful information regarding the Arctic regions is given in the 'Manual and Instructions for the Arctic Expedition,' 1875.

There is proof also that the glaciers of New Zealand were formerly much larger.[1]

As De la Beche has well pointed out, the student must be on his guard lest he be led to mistake for true erratics mere weathered blocks belonging to a rock that has disintegrated *in situ.* If, for example, he should encounter a block like that represented in Fig. 154, he would properly conclude that it had travelled, because it did not belong to the rock on which it lay. But he would require to prove further that there was no rock in the immediate neighbourhood from which it could have fallen as the result of mere weathering. The granite (*c*) shown in Fig. 155 disintegrates at the summit, and the blocks into which it splits find their way by gravitation down the slope.[2]

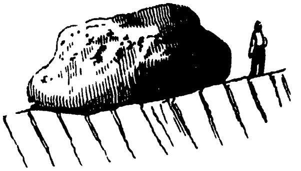

Fig. 154.—Block of granite resting on inclined strata (*B.*)

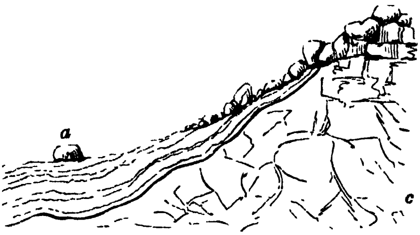

Fig. 155.—Granite (*c*) decomposing into blocks (*a*), which gradually roll down upon the surrounding stratified rocks (*B.*)

(*b*) *Erosion.*—The manner and results of erosion in the channel of a glacier differ from those associated with other geological agents, and form therefore distinguishing features of ice-action. This erosion is effected not by the mere contact and pressure of the ice upon the rocks (though undoubtedly blocks of rock may thereby be detached), but by means of the fine sand, stones, and blocks of rock that fall between the ice and the rocks on which it moves. The detritus thus introduced is, for the most part, fresh and angular. Its trituration by the glacier reduces the size of the particles, but retains their angular character, so that, as Daubrée has pointed out, the sand that escapes from the end of a glacier appears in sharp freshly-broken grains, and not as rounded water-worn particles.[3]

The surface of a glacier being often strewn with earth and stones, these materials are frequently precipitated into the crevasses, and may thus reach the rocky floor over which the ice is moving. They likewise fall

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[1] For New Zealand glaciers see A. P. Harper, *Geograph. Journ.* i. (1893), p. 32.

[2] De la Beche, 'Geological Observer,' p. 257. The surface of some parts of the granite districts of Cornwall are strewn with large boulders of granite, schorl-rock, vein-quartz, &c., but these, though resembling erratics in form, are all due to decomposition of the parent-rocks *in situ.*

[3] 'Géologie Expérim.' p. 254.

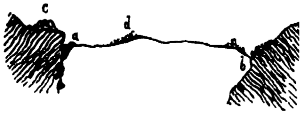

Fig 156 —Section of a Glacier in its rocky channel,

With a medial moraine at *d*, a lateral moraine partly on the ice and partly stranded on a sloping declivity (*b*), a mass of rocks fallen between the ice and the precipitous rocks at *a*, and a group of perched blocks at *c* (J D Forbes)

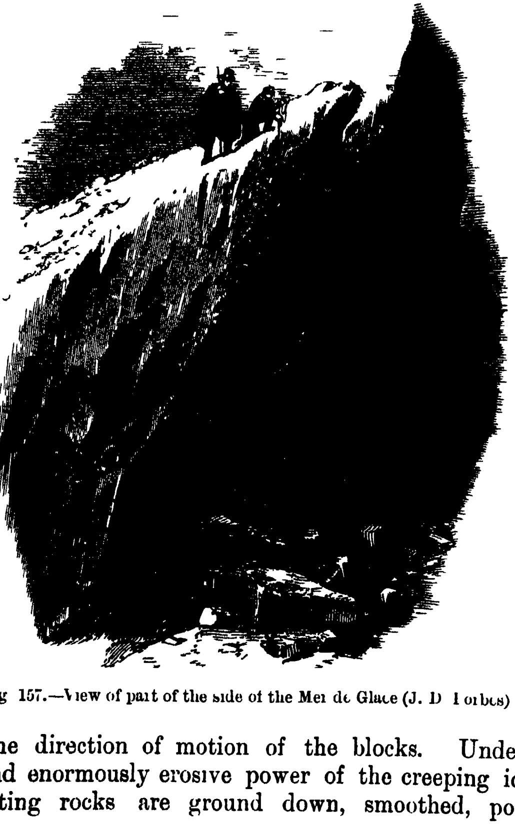

Fig 157.—View of part of the side of the Mer de Glace (J. D Forbes)

into the narrow space which sometimes intervenes between the margin of a glacier and the side of the valley (*a* in Fig. 156). Held by the ice as it creeps along, they are pressed against the rocky sides and bottom of the valley so firmly and persistently as to descend into each little hollow and mount over each ridge, yet all the while moving along steadily in one dominant direction with the general movement of the glacier. Here and there the ice, with grains of sand and pieces of stone imbedded in its surface, can be caught in the very act of polishing and scoring the rocks. In Fig 157 a view is given of the "angle" on the Mer de Glace, Chamouni, where blocks of granite are jammed between the mural edge of the ice and the precipice of rock along which it moves, and which is scored and polished in the direction of motion of the blocks. Under the slow, continuous, and enormously erosive power of the creeping ice, the most compact resisting rocks are ground down, smoothed, polished, and striated (Fig. 158). The striæ vary from such fine lines as may be made by the smallest grains of quartz up to deep ruts and grooves. They sometimes cross each other, one set partially effacing an older one, and thus pointing to shiftings in the movement of the ice. On the retirement of the glacier, hummocky bosses of rock, having smooth undulating forms like dolphins' backs, are conspicuous. These have received the name of *roches moutonnées*. The stones by which this scratching and polishing are effected suffer in exactly the same way. They are ground down and striated, and since they must move in the line of least resistance, or "end on," their striæ run in a general sense lengthwise (Fig. 160). It will be seen, when we come to notice the traces of former glaciers, how important is the evidence given by these striated stones.

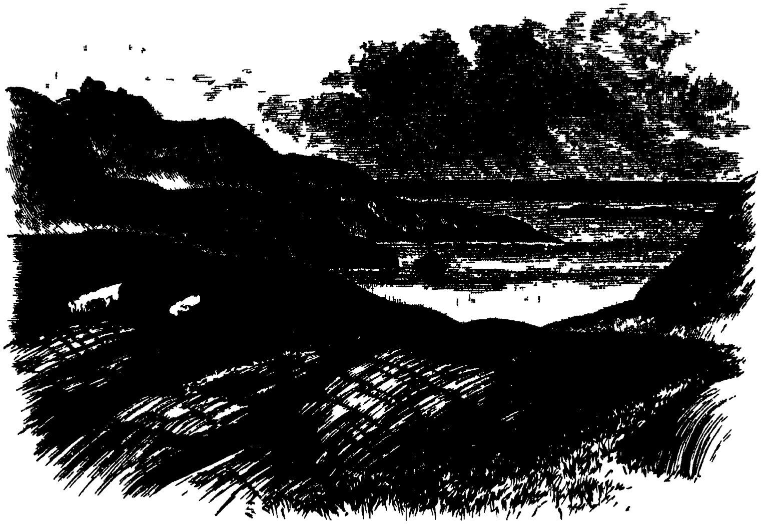

Fig. 158. Ice-worn surface of rock, showing Polish, Striæ, Groovings, and Erratics, Sutherland.

Besides its proper and characteristic rock-erosion, a glacier is aided in a singular way by the co-operation of running water. Among the Alps, during day in summer, much ice is melted, and the water courses over the glaciers in brooks which, as they reach the crevasses, tumble down in rushing waterfalls, and are lost in the depths of the ice. Directed, however, by the form of the ice-passage against the rocky floor of the valley, the water descends at a particular spot, carrying with it the sand, mud, and stones which it may have swept away from the surface of the glacier. By means of these materials it erodes deep pot-holes (moulins) in the solid rock, in which the rounded detritus is left as the crevasse closes up or moves down the valley. On the ice-worn surface of Norway, singular cavities of this kind, known as "giants' kettles" or "cauldrons"

(Riesentöpfe, Riesenkessel, Fig. 159), exist in great numbers.[1] There can be little doubt that they have had an origin under the massive ice-cover which once spread over that peninsula. Similar cavities filled with transported boulders occur in the molasse sandstone near Bern,[2] and a large group of them is now one of the sights of Lucerne. They have been recognised in North Germany[3] and generally over the glaciated areas of Europe. As the Greenland ice-sheet is traversed in summer by powerful rivers which are swallowed up in the crevasses, excavations of the same nature are no doubt also in progress there.

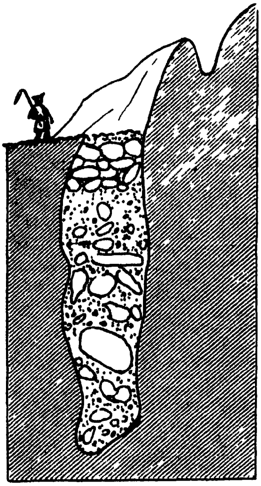

Fig. 159.—Section of "Giant's Kettle," near Christiania.

Since rocks present great diversities of structure and hardness, and consequently vary much in the resistance they offer to denudation, they are necessarily worn down unequally. The softer, more easily eroded portions are scooped out by the grinding action of the ice, and basin-shaped or various irregular cavities are dug out below the level of the general surface. Similar effects may be produced by a local augmentation of the excavating power of a glacier, as where the ice is strangled in some narrow part of a valley, or where, from change in declivity, it is allowed to accumulate in greater mass as it moves more slowly onward. Such hollows, on the retirement of the ice, become receptacles for water, and form pools, tarns, or lakes, unless, indeed, they chance to have been already filled up with glacial rubbish.

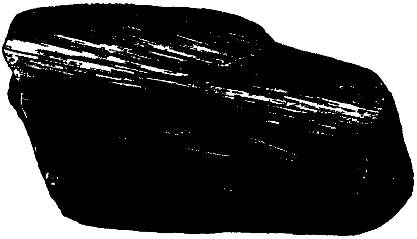

Fig. 160.—Striated stone from Boulder-Clay.

Among the proofs of great erosion by ice on hard rocky surfaces the existence of basins scooped out of the solid rock are perhaps the most striking. The striæ and scorings may in such cases be traced down below the water at the end of a tarn or lake, and may be found emerging at the other end with the same steady direction as on the surrounding ground or enclosing valley. In the year 1862 the late Sir A. C. Ramsay drew attention to this peculiar power of land-ice, and affirmed that the abundance of excavated rock-basins in Northern Europe and America, was due to the fact that these regions had been extensively eroded by sheets of land-ice, when the more northern parts of the two continents were in a condition like that of North Greenland at the present day.[1] It is among the ice-fields of Greenland, rather than among the valley-glaciers of isolated mountain-groups, that the operations which produced the widespread general glaciation of the period of the rock-basins find their nearest modern analogies. A single valley-glacier retires towards its parent snow-field as the climate ameliorates, leaving its *roches moutonnées*, moraine-mounds, and rock-basins, yet at times discharging its water-drainage in such a way as to sweep down the moraine-mounds, fill up the basins, bury the ice-worn hummocks of rock, and strew the valley with gravel, earth, sand and big blocks of rock. Hence the actual floor of the glacier is apt to be obscured. But in the case of a vast sheet of land-ice covering continuously a wide region, there can be but little superficial débris. When such a mass of ice retires, it must leave behind it an ice-worn surface of country, more or less strewn with the detritus which accumulated under the ice and was pushed along by it. This infra-glacial débris forms the *Grundmorane* (*moraine profonde*), or bottom-moraine above referred to (p. 425). We know as yet very little regarding its formation in Greenland. Most of our knowledge regarding it is derived from a study of the till or boulder-clay in more southern latitudes, which is believed to represent the bottom-moraine of an ancient ice-sheet. In countries where true boulder-clay occurs, numerous rock-basins are commonly to be met with among the uncovered portions of the rocks. These and other features of glaciated Europe and America will be more fully described in the account of the Glacial Period (Book VI.)[2]

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[1] S. A. Sexe, *Universit. Program. Christiania*, 1874. Brögger and Reusch, *Q. J. Geol. Soc.* xxx. 750.

[2] Bachmann, *Neues Jahrb.* 1875, p. 53.

[3] *Jahrb. Preuss. Geol. Landesanst.* 1880, p. 275.

But while the proofs of great erosion by land-ice are indisputable, many instances have now been collected where glaciers have over-ridden moraines, gravel-beds, or other soft material, and have moved across them for perhaps long periods without removing them. It is obvious that in these places the ice can have no marked or at least rapid erosive power. The preservation of detritus below the ice seems generally to arise from flatness of the ground, thinning away of the ice, or some other local cause sufficient to indicate that the glacier cannot there act with erosive effect.[1]

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[1] *Q. J. Geol. Soc.* xviii. (1862), p. 185. See also a paper by A. Helland (*op. cit.* xxxiii. p. 142), on the Ice-fjords of North Greenland, and the formation of Fjords, Lakes, and Cirques. That glaciers rub down rocks is demonstrated by the *roches moutonnées* which they leave behind them. That they can dig out hollows has been denied by some able observers, but that they can do so to some extent at least, seems to be proved by the way in which the ice-striæ descend into and rise out of rock-basins. For arguments against this view see especially W. D. Freshfield, *Proc. Roy. Geog. Soc.* 1888, p. 779, and authorities there cited.

[2] See the remarks already made (p. 351) on the possibility of the rotting out of basin-shaped receptacles in solid rock through the operations of superficial weathering—a process which may account for many rock-basins that have subsequently had their decomposed rock swept out of them by ice.

Hardly anything has yet been done in the way of actual measurement of the rate of erosion by different glaciers. An approximation to the truth might be obtained from the abundant fine sediment which, giving the characteristic milky turbidity to all streams that escape from the melting ends of glaciers, is an index of the amount of this erosion. The average quantity of sediment discharged from the melting end of a glacier during a year having been estimated, it would be easy to determine its equivalent in the precise fraction of a foot of rock annually removed from the area drained by the glacier.

From the end of the Aar glacier (which with its affluents is computed to have an area of 60 square kilometres, and is therefore by no means one of the largest in Switzerland) it has been estimated that there escape every day in the month of August two million cubic metres (440 million gallons) of water, containing 284,374 kilogrammes (280 tons) of sand. The amount of fine sand discharged from the melting glacier into the fjord of Isortok, Greenland, is estimated at 4062 million kilogrammes per day.[2] Mr. A. Helland has computed that from the Justedal glacier, Norway, one million kilogrammes of sediment are discharged in a July day, and that the total annual discharge from the ice-field, 830 square miles in area, amounts to 180 millions of kilogrammes, besides 13 million kilogrammes of mineral matter in solution Taking the specific gravity of the suspended matter at 2·6, he finds that the basin of the glacier loses 69,000 cubic metres of solid rock every year, or a cubic mass measuring 41 metres on the side.[3] There is some difficulty, however, in determining what proportion of the sediment may have been washed in below the ice by streams issuing from springs and melted snows. Estimates of the work done by glaciers, so far as based upon the amount of sediment discharged by them, may consequently be rather over the truth.

§ 6. Oceanic Waters.

The area, depth, temperature, density, and composition of the sea having been already treated of (Book II.), we have now to consider its place among the dynamical agents in geology. In this relation it may be studied under two aspects: 1st, its movements, and 2nd, its geological work.

I. **Movements.**—(1) *Tides.*—These oscillations of the mass of the oceanic waters, caused by the attraction of the sun and moon, require notice here only as regards their geological bearings. They are scarcely perceptible in enclosed seas, such as the Mediterranean and Black Seas, which are commonly spoken of as tideless. In strictness, however, a feeble but quite recognisable tide may be observed in the Mediterranean. On the coast of the Alpes Maritimes it has a mean rise of 6 to 8 inches, the least rise being 4 and the highest not exceeding 10 inches. The Mediterranean tides are most strongly developed in the Bay of Gibraltar (where they rise from 5 feet to 6 feet 6 inches), the upper Adriatic, and the Gulf of Gabes. At Brindisi the rise is 8 inches, at Ancona 1 foot 4 inches, at Venice 1 foot 8 inches, and at Trieste 2 feet 4 inches. With a rise of the barometer the level of the water falls sometimes a fourth lower than the limit of the normal ebb. Observations at Nice, Monaco, Cannes, and other places show that from atmospheric disturbances the level of the sea may be lowered as much as 1 foot 8 inches.[1]

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[1] For a striking example of the way in which a glacier may spread over deposits of gravel, see the plate accompanying Mr. H. P. Cushing's paper on the Muir Glacier of Alaska, *American Geologist*, 1891.

[2] Meddelelser om Grønland, vol. ii.

[3] *Geol. Fören. Stockholm Förhandl.* 1874, No. 21, Band ii. No. 7.

In a wide deep ocean, tidal elevation probably produces no perceptible geological change. It passes at a great speed; in the Atlantic, its rate is 500 geographical miles an hour. But as this is merely the passing of an oscillation whereby the particles of water are gently raised up and let down again, there can hardly be any appreciable effect upon the deep ocean-bottom. When, however, the tidal wave enters a narrow and shallow sea, it has to accommodate itself to a smaller channel, and encounters more and more the friction of the bottom. Hence, while its rate of motion is diminished, its height and force are increased. It is in shallow water, and along the shores of the land, that the tides acquire their main geological importance. They there show themselves in an alternate advance upon and retreat from the coast. Their upper limit has received the name of *high-water mark*, their lower that of *low-water mark*, the littoral space between being termed the *beach* (Fig. 161). If the coast is precipitous, a beach can only occur in shelving bays and creeks, since elsewhere the tides will rise and fall against a face of rock, as they do on the piers of a port. On such rocky coasts, the line of high-water is sometimes admirably defined by the grey crust of barnacles adhering to the rocks. Where the beach is flat, and the rise and fall of the tide great, many square miles of sand or mud may be laid bare in one bay at low-water.

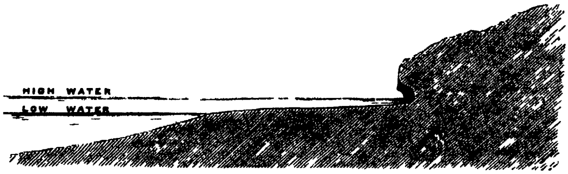

Fig. 161.—Section of a Beach defined by High- and Low-Water Mark.

The height of the tide varies from zero up to 60 or 70 feet. It is greatest where, from the form of the land, the tidal wave is cooped up within a narrow inlet or estuary. Under such circumstances the advancing tide sometimes gathers itself into one or more large waves, and rushes furiously up between the converging shores. This is the origin of the "bore" of the Severn, which rises to a height of 9 feet, while the rise and fall of the tide at Chepstow amounts to a maximum of 50 feet. In like manner, the tides which enter the Bay of Fundy, between Nova Scotia and New Brunswick, are more and more cooped up and rise higher as they ascend that strait, till they reach a height of 70 feet. The bore on the Tsien-Tang Kiang, 70 miles from Shanghai, rushes up the estuary as a huge breaker 20 feet or more in height, with a loud roar and a speed of sometimes eight knots an hour.[1]

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[1] Haschert, *Deutsche Rundschau für Geographie*, July 1887. *Bull. Amer. Geograph. Soc.* xix. (1887), p. 314. J. de Pulligny, *Assoc. Franç.* 1891, ii. p. 287

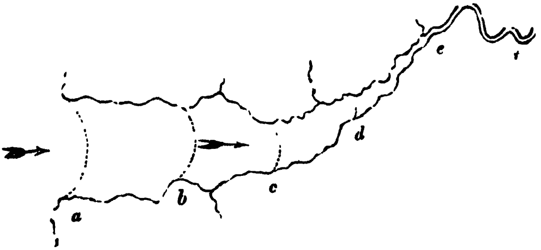

Fig. 162.—Effect of converging shores upon the Tidal Wave.
The tidal wave, running up in the direction of the arrows, rises successively higher at *a*, *b*, and *c* to *d*, after which it slackens and dies away at the upper limit of tides, *f*.

While the tidal swelling is increased in height by the shallowness and convergence of the shores between which it moves, it gains at the same time force and rapidity. No longer a mere oscillation or pulsation of the great ocean, the tide acquires a true movement of translation, and gives rise to currents which rush past headlands and through narrows in powerful streams and eddies.

The rocky and intricate navigation of the west of Scotland and Scandinavia furnishes many admirable illustrations of the rapidity of these tidal currents. The famous whirlpool of Corryvreckan, the lurking eddies in the Kyles of Skye, the breakers at the Bore of Duncansby, and the tumultuous tideway, grimly named by the northern fishermen "the Merry Men of Mey," in the Pentland Firth, bear witness to the strength of these sea rivers. At the last-mentioned strait, the current or "race" at its strongest runs at the rate of 10 miles an hour, which is fully three times the speed of most of our large rivers

(2) *Currents.*—Recent researches in ocean-temperature have disclosed the remarkable fact that, beneath the surface-layer of water affected by the temperature of the latitude, there lies a vast mass of cold water, the bottom-temperature of every ocean in free communication with the poles being little above, and sometimes actually below, the freezing-point of fresh water.[2] In the North Atlantic, a temperature of 40° Fahr. is reached at an average depth of about 800 fathoms, all beneath that depth being progressively colder. In the equatorial parts of that ocean, the same temperature comes to within 300 fathoms of the surface. In the South Atlantic, off Cape of Good Hope, the mass of cold water (below 40°) rises likewise to about 300 fathoms from the surface. This distribution of temperature proves that there must be a transference of

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[1] Report to the Admiralty by Commander Moore, R.N., 1888.

[2] See, in particular, memoirs by Carpenter and Wyville Thomson, *Proc. Roy. Soc.* xvii. (1868); *Brit. Assoc.* xli. *et seq.*; *Proc. Roy. Geograph. Soc.* xv. Reports to the Admiralty of the *Challenger* Exploring Expedition. Wyville Thomson's 'Depths of the Sea,' 1873, and 'Atlantic,' 1877. Narrative volume of '*Challenger*' *Report.* Prince of Monaco, *Brit. Assoc.* 1892.

cold polar water towards the equator, for in the first place, the temperature of the great mass of the ocean is much lower than that which is normal to each latitude, and in the second place, it is much lower than that of the superficial parts of the earth's crust underneath. On the other hand, the movement of water from the poles to the equator requires a return movement of compensation from the equator to the poles, and this must take place in the superficial strata of the ocean. Apart therefore from those rapid river-like streams which traverse the ocean, and to which the name of Currents is given, there must be a general drift of warm surface-water towards the poles. This is doubtless most markedly the case in the North Atlantic, where, besides the current of the Gulf Stream, there is a prevalent set of the surface-waters towards the north-east. As the distribution of life over the globe is everywhere so dependent upon temperature, it becomes of the highest interest to know that a truly arctic submarine climate exists everywhere in the deeper parts of the sea. With such uniformity of temperature, we may anticipate that the abysmal fauna will be found to possess a corresponding sameness of character, and that arctic types may be met with even on the ocean-bed at the equator.

But besides this general drift or set, a leading part in oceanic circulation is taken by the more defined currents. The tidal wave only becomes one of translation as it passes into shallow water, and is thus of merely local consequence. But a vast body of water, known as the Equatorial Current, moves in a general westerly direction round the globe. Owing to the way in which the continents cross its path, this current is subject to considerable deflections. Thus, that portion which crosses the Atlantic from the African side strikes against the mass of South America, and divides, one portion turning towards the south and skirting the shores of Brazil; the other bending north-westward into the Gulf of Mexico, and issuing thence as the well-known Gulf Stream. This equatorial water is comparatively warm and light. At the same time, the heavier and colder polar water moves towards the equator, sometimes in surface-currents like those which skirt the eastern and western shores of Greenland, but more generally as a cold under-current which creeps over the floor of the ocean even as far as the equator.

A large body of information has now been gathered as to the great marine currents which traverse the upper parts of the ocean, but comparatively little is yet known of the velocity of the movement of the water at great depths. Where the bottom is covered with a deep fine ooze we may infer that the rate of movement must be so feeble as not to disturb the deposition of the finest sediment. Where, on the other hand, "hard-bottom" is found, we may probably conclude that a sufficiently strong current flows there to prevent the accumulation of sediment, for all over the ocean there is enough of organic and inorganic particles diffused through the water to form a deposit on the floor if the conditions are favourable A few observations have been made showing that at considerable depths among submarine ridges or islands strong currents exist. At a depth of 3000 feet near Gibraltar the telegraph cable from Falmouth was ground like the edge of a razor, and the scouring effects of strong currents have been noted at depths of 6000 feet between the Canary Islands.[1]

Much discussion has arisen in recent years as to the cause of oceanic circulation. Two rival theories have been given. According to one of these, the circulation entirely arises from that of the air. The trade-winds, blowing from either side of the equator, drive the water before them until the north-east and south-east currents unite in equatorial latitudes into one broad westerly-flowing current. Owing to the form of the land, portions of this main current are deflected into temperate latitudes, and, as a consequence, an equivalent bulk of polar water requires to move towards the equator to restore the equilibrium. According to the other view, the currents arise from differences of temperature (and according to some, of salinity also); the warm and light equatorial water stands at a higher level than the colder and heavier polar water; the former, therefore, flows down as it were polewards, while the latter moves as a bottom-inflow towards the equator; the cold bottom-water under the tropics slowly ascends to the warmer upper layers, and rises in temperature towards the surface, whence it drifts away as warm water towards the pole, and, on being cooled down there, descends and begins another journey to the equator. There can be no doubt that the winds are directly the cause of such currents as the Gulf Stream, and therefore, indirectly, of return cold currents from the polar regions. It seems hardly less certain that, to some extent at least, differences of temperature, and therefore of density, must occasion movements in the mass of the oceanic waters.[2]

Apart from disputed questions in physics, the main facts for the geological reader to grasp are—that a system of circulation exists in the ocean; that warm currents move round the equatorial regions, and are turned now to the one side, now to the other, by the form of the continents along and around which they sweep; that cold currents set in from poles to equator; and that, apart from actual currents, there is an extremely slow "creep" of the polar water, under the warmer upper layers, to the equator.

(3) *Waves and Ground-Swell.*—A gentle breeze curls into ripples the surface of water over which it blows. A strong gale or furious storm raises the surface into waves. The agitation of the water in a storm is prolonged to a great distance beyond the area of the original disturbance, and then takes the form of the long heaving undulation termed *Ground-swell.* Waves which break upon the land or sunken rocks are called *Breakers*, and the same name is applied to the ground-swell as it

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[1] T. M. Reade, *Phil. Mag.* xxv. (1888), p. 342.

[2] The student may consult Maury's 'Physical Geography of the Sea,' but more particularly Dr. Carpenter's papers in the *Proceedings of the Royal Society* for 1869-73, and *Journal of the Royal Geographical Society* for 1871-77, on the side of temperature; and Herschel's 'Physical Geography,' and Croll's 'Climate and Time,' on the side of the winds.

bursts into foam and spray upon submarine reefs and shoals. The concussion of earthquakes sometimes gives rise to very disastrous ocean-waves (pp. 271, 278).

The height and force of waves depend upon the strength and continuance of the wind, the breadth and depth of sea, and the form and direction of the coast-line. The longer the "fetch," and the deeper the water, the higher the waves. A coast directly facing the prevalent wind will have larger waves than a neighbouring shore which presents itself at an angle to the wind or bends round so as to form a lee-shore. The highest waves in the narrow British seas probably never exceed 15 or 20 feet, and usually fall short of that amount. The greatest height observed by Scoresby among the Atlantic waves was 43 feet.[1]

Ground-swell propagated across a broad and deep ocean produces by far the most imposing breakers. So long as the water remains deep and no wind blows, the only trace of the passing ground-swell on the open sea is the huge broad heaving of the surface. But where the water shallows, the superficial part of the swell, travelling faster than the lower, which encounters the friction of the bottom, begins to curl and crest as a huge billow or wall of water, that finally bursts against the shore. Such billows, even when no wind is blowing, often cover the cliffs of the north of Scotland with sheets of water and foam up to heights of 100 or even nearly 200 feet. During north-westerly gales, the windows of the Dunnet Head lighthouse, at a height of upwards of 300 feet above high-water mark, are said to be sometimes broken by stones swept up the cliffs by the sheets of sea-water which then deluge the building.

A single roller of the ground-swell 20 feet high falls, according to Mr. Scott Russell, with a pressure of about a ton on every square foot. Mr. Thomas Stevenson conducted some years ago a series of experiments on the force of the breakers on the Atlantic and North Sea coasts of Britain. The average force in summer was found in the Atlantic to be 611 lb. per square foot, while in the winter it was 2086 lb., or more than three times as great. On several occasions, both in the Atlantic and North Sea, the winter breakers were found to exert a pressure of three tons per square foot, and at Dunbar as much as three tons and a half.[2] Besides the waves produced by ordinary wind action, others of an extraordinary size and destructive power are occasionally caused by local atmospheric disturbances. Such are probably the *raz de marée* of the French coast, which occasionally rise to a height of several feet, and, where the shores converge inland, do considerable damage. Still more serious are the effects of a violent cyclone-storm. The mere diminution of atmospheric pressure in a cyclone must tend to raise the level of the ocean within the cyclone limits. But the further furious spiral in-rushing of the air towards the centre of the low-pressure area drives the sea onward, and gives rise to a wave or succession of waves having great destructive power. Thus, on 5th October 1864, during a great cyclone which passed over Calcutta, the sea rose in some places 24 feet, and swept everything before it with irresistible force, drowning upwards of 48,000 people.

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[1] *Brit. Assoc. Rep.* 1850, p. 26. A table of the observed heights of waves round Great Britain is given in Mr. T. Stevenson's treatise on 'Harbours,' p. 20.

[2] T. Stevenson, *Trans. Roy. Soc. Edin.* xvi. p. 25; treatise on 'Harbours,' p. 42.

Besides the height and force of waves it is important to know the depth to which the sea is affected by such superficial movements. Sir G. Airy states that ground-swell may break in 100 fathoms water.[1] It is common to find boulders and shingle disturbed at a depth of 10 fathoms, and even driven from that depth to the shore, and waves may be noticed to become muddy from the working-up of the silt at the bottom, when they have reached water of 7 or 8 fathoms in depth.[2] In the English Channel coarse sediment is disturbed at depths of 30 or more fathoms.[3] It is stated by Delesse that engineering operations have shown submarine constructions to be scarcely disturbed at a greater depth than 5 metres (16·4 feet) in the Mediterranean and 8 metres (26·24 feet) in the Atlantic.[4] In the Bay of Gascony, the depth at which the sea breaks and is effective in the transport of sand along the bottom, is said to vary from scarcely 3 metres in ordinary weather to 5 metres in stormy weather, and only exceeds 10 metres (32·8 feet) in great hurricanes. According to Commander Cialdi, the movement of waves may disturb fine sand on the bottom at a depth of 40 metres (131 feet) in the English Channel, 50 metres (164 feet) in the Mediterranean, and 200 metres (656 feet) in the ocean.[5] Off the Florida coast the disturbing action of the waves is believed to cease below 100 fathoms.[6] As above remarked, the influence of currents has been detected at much greater depths.

(4) *Ice on the Sea.*—In this place may be most conveniently noticed the origin and movements of the ice which in circumpolar latitudes covers the sea. This ice is derived from two sources—*α*, the freezing of the sea itself, and *β*, the seaward prolongation of land-ice.[7]

α. Three chief types of sea-ice have been observed. (*a*) In the Arctic sounds and bays, the littoral waters freeze along the shores, and form a cake of ice which, upborne by the tide and adhering to the land, is thickened by successive additions below, as well as by snow above, until it forms a shelf of ice 120 to 130 feet broad, and 20 to 30 feet high. This shelf, known as the Ice-foot, serves as a platform on which the abundant débris, loosened by the severe frosts of an Arctic winter, gathers at the foot of the cliffs. It is more or less completely broken up in summer, but forms again with the early frosts of the ensuing autumn (*b*) The surface of the open sea likewise freezes over into a continuous solid sheet, which, when undisturbed, becomes in the Arctic regions about eight feet thick, but which in summer breaks up into separate masses, sometimes of large extent, and is apt to be piled up into huge, irregular heaps (Fig. 163). This is what navigators term Floe-ice, and the separate floating cakes are known as *floes* Ships fixed among these floes have been drifted with the ice for hundreds of miles, until at last liberated by its disruption. (*c*) In the Baltic Sea, off the coast of Labrador and elsewhere, ice has been observed to form on the sea-bottom It is known as Ground-ice or Anchor-ice. In the Labrador fishing-grounds, it forms even at considerable depths. Seals caught in the lines at those depths are said to be brought up sometimes solidly frozen [1]

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[1] *Encyclopedia Metropolitana*, art. "Waves." Gentle movement of the bottom water is said to be sometimes indicated by ripple-marks on the fine sand of the sea-floor at a depth of 600 feet.

[2] T. Stevenson's 'Harbours,' p. 15.

[3] A. R. Hunt, *Proc. Roy. Dublin Soc.* iv. (1884), p. 285. For further information on this subject see *postea*, pp. 451, 455.

[4] 'Lithologie des Mers de France' (1872), p. 110.

[5] Quoted by Delesse, *op. cit.* p. 111.

[6] A. Agassiz, *Amer. Acad.* xii. (1882), p. 108.

[7] Consult on the whole of this subject K. Weyprecht's 'Die Metamorphosen des Polareises,' Vienna, 1879; Payer's 'New Lands within the Arctic Circle,' 1876, chap. i. The physics of sea-ice are discussed by O. Pettersson ('Vega-Expeditionens Vetenskapliga Iakttagelser,' ii. p. 299, Stockholm, 1883), who concludes that instead of being contracted by cold, the volume of the frozen sea increases to an extraordinary degree, and that the rupture of the ice is thus due to expansion instead of contraction.

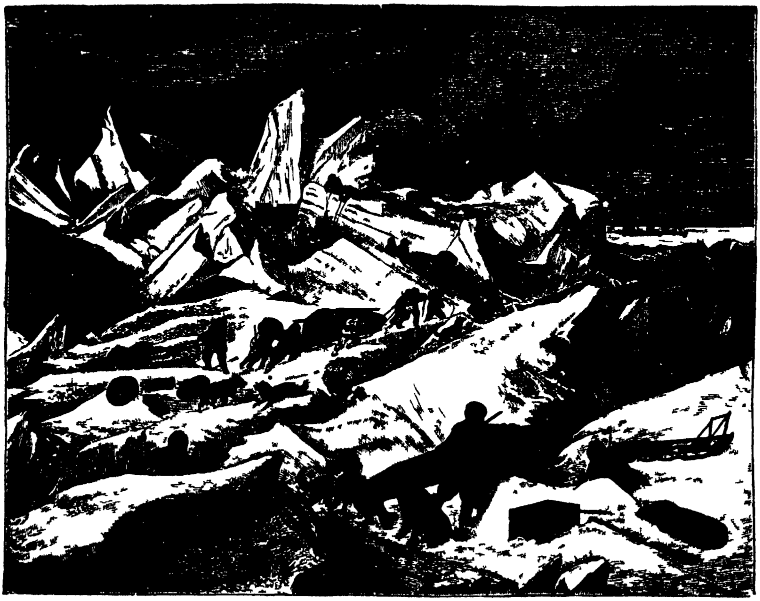

Fig 163 —Disrupted Floe ice of Arctic Seas

β. In the Arctic regions, vast glaciers drain the snow-fields, and, descending to the sea, extend for some distance from shore until large fragments break off and float away seawards (Fig. 164). These detached masses are Icebergs. Their shape and size greatly vary, but lofty peaked forms are common (Fig. 165), and they sometimes rise from 200 to 300 feet above the level of the sea. As the part that appears above water is only about one-ninth of the whole mass of ice, these larger bergs may sometimes be from 1800 to 2700 feet thick from base to top, though the submarine part of the ice may be as irregular in form and thickness as the portion above water.[1] Icebergs of the largest size consequently require water of some depth to float them, but are sometimes seen aground. In the Antarctic regions, where one vast sheet of ice envelops the land and protrudes into the sea as a long, lofty rampart of ice, the detached icebergs often reach a great size, and are characterised by the frequency of a flat tabular form (Fig. 166).

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[1] See H. Y. Hind, *Canadian Naturalist*, viii. (1878), pp 227, 262

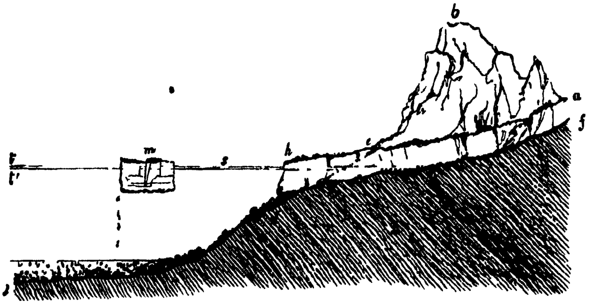

Fig 164 – Formation of Icebergs (*B*)

The glacier (*a*, *h*) descends from mountainous ground (*b*) to the sea-level (*s*), bearing moraine stuff on the surface, pushing on detritus below (*d*), and sending off icebergs (*m*), which may carry detritus and drop it over the sea-bottom; *t*, *t'*, *g*, lines of high and low water

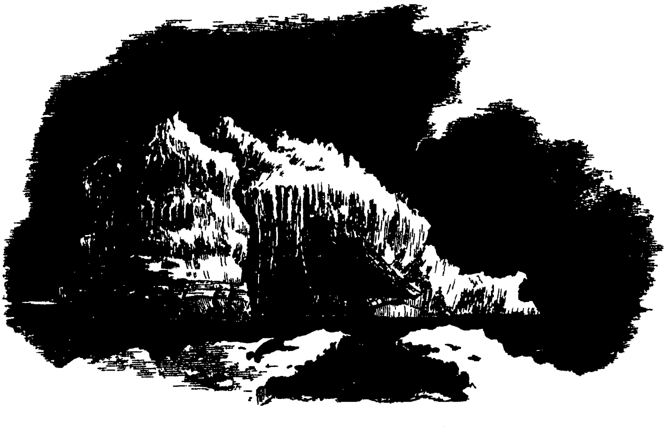

Fig 165 — Arctic Iceberg seen on Parry's first voyage

II. **Geological Work.**—(1) Influence on Climate.—Were there no agencies in nature for distributing temperature, there would be a regular and uniform diminution in the mean annual temperature from equator to poles, and the *isothermal* lines, or lines of equal heat, would coincide with lines of latitude. But no such general correspondence actually exists. A chart of the globe, with the isothermal lines drawn across it, shows that their divergences from the parallels are striking, and most so where they approach and cross the ocean. Currents from warm regions raise the temperature of the tracts into which they flow; those from cold regions lower it. The ocean, in short, is the great distributor of temperature over the globe.

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[1] On flotation of icebergs, see *Geol. Mag.* (2nd sec.), iii. p. 303, 379; iv. 65, p. 135.

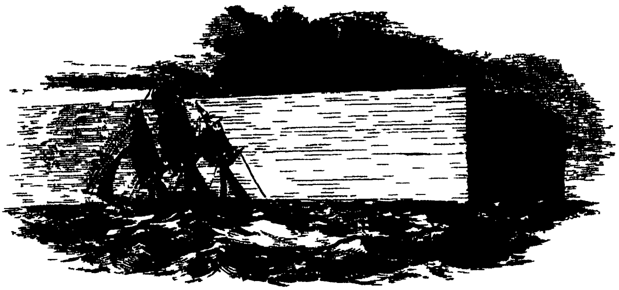

Fig. 166.—Tabular Iceberg detached from the great Antarctic Ice barrier. (Wilkes.)

As an illustration, the two opposite sides of the North Atlantic may be taken. The cold Arctic current, flowing southward along the north-east coast of America, reduces the mean annual temperature of that region. On the other hand, the Gulf Stream brings to the shores of the north-west of Europe a temperature much above what they would otherwise enjoy. Dublin and the south-eastern headlands of Labrador lie on the same parallel of latitude, yet differ as much as 18° in their mean annual temperature, that of Dublin being 50°, and that of Labrador 32° Fahr. Dr. Croll has calculated that the Gulf Stream conveys nearly half as much heat from the tropics as is received from the sun by the entire Arctic Regions.[1]

(2) Erosion. A. *Chemical.*—The chemical action of the sea upon the rocks of its bed and shores has not yet been properly studied.[2] It is evident, however, that changes analogous to those effected by fresh water on the land must be in progress. Oxidation, solution, and the formation of carbonates, no doubt continually take place. The solvent action of sea-water on calcareous organisms, already referred to (p. 38), has in recent years been made the subject of discussion and experiment. Dr. Murray, in calling attention to the gradual disappearance of such organisms, as the deposits of the sea-bottom are traced down into the abysses, explained it by the solvent influence of the water containing

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[1] See a series of papers by him on the "Gulf Stream and Ocean Currents," in *Geol. Mag.* and *Phil. Mag.* for 1869, 1870-74, and his work 'Climate and Time'; likewise a series of controversial papers on this subject by him and Prof. Newcombe, *Phil. Mag.* 1883-4. Prof. Haughton has offered some calculations of the actual amount of influence exercised by ocean-currents upon climate, and of the effect of a current between the Indian and Arctic Oceans across Mesopotamia and the Aralo-Caspian depression. *Brit. Assoc.* 1881, Reports, pp. 451-463.

[2] See Bischof's 'Chemical Geology,' vol. i. chap. vii.

carbonic acid in solution, and he has more recently conducted a series of experiments to demonstrate the truth of this view. Ten specimens of coral of different species were immersed in sea-water and allowed to remain for periods varying from 20 to 60 days. In each case a perceptible loss of material took place, varying from 0·0725 to 0·1707 of their weight, which he estimated to be equal to a rate of loss amounting to from 0·453 to 0·1860 from one square inch of surface in a year. The more areolar or amorphous corals were attacked more rapidly than the harder crystalline varieties.[1] The complex chemical changes that take place in the sea through the operation of living and dead organisms are referred to on pp. 482, 484, 492, 493.

We may judge, indeed, of the nature and rapidity of some of these changes by watching the decay of stones and material employed in the construction of piers. Mr. Mallet—as the result of experiments with specimens sunk in the sea—concluded that from $\frac{2}{10}$ to $\frac{4}{10}$ of an inch in depth in iron castings 1 inch thick, and about $\frac{6}{10}$ of an inch of wrought iron, will be destroyed in a century in clear salt water. Mr. Stevenson, in referring to these experiments, remarks that at the Bell Rock lighthouse, twenty-five different kinds and combinations of iron were exposed to the action of the sea, and all yielded to corrosion. In some of these castings, the loss has been at the rate of an inch in a century. "One of the bars which was free from air-holes had its specific gravity reduced to 5·63, and its transverse strength from 7409 lb. to 4797 lb., and yet presented no external appearance of decay. Another apparently sound specimen was reduced in strength from 4068 lb. to 2352 lb., having lost nearly half its strength in fifty years."[2] Similar results were observed by Mr. Grothe, resident engineer at the construction of the ill-fated railway bridge across the Firth of Tay. A cast-iron cylinder (such as was employed in constructing the concrete basements for the piers), which had been below water for only sixteen months, was found to be so corroded that a penknife could be stuck through it in many places. An examination of the shore will sometimes reveal a good deal of quiet chemical change on the outer crust of wave-washed rocks. Basalt, for instance, has its felspar decomposed, and shows the presence of carbonates by effervescing briskly with acid. The augite is occasionally replaced by ferrous carbonate. The solvent action of sea-water on calcareous organisms is referred to on pp. 38, 491.

B. *Mechanical.*—It is mainly by its mechanical action that the sea accomplishes its erosive work. This can only take place where the water is in motion, and, other things being equal, is greatest where the motion is strongest. Hence we cannot suppose that erosion to any appreciable extent can be effected in the abysses of the sea, where the only motion is probably the slow creeping of the polar water. But where the currents are powerful enough to move grains of sand and gravel, a slow erosion may take place even at considerable depths. It is in the upper portions of the sea, however,—the region of currents, tides, and waves,—that mechanical erosion is chiefly performed. The depth to which the influence of waves and ground-swell may extend seems to vary greatly according to the situation (*ante*, p. 438). A good test for the absence of serious abrasion is furnished by the presence of fine mud on the bottom. Wherever that is found, we may be tolerably sure that the bottom at that place lies beyond the reach of ordinary breaker-action.[1] From the superior limit of the accumulation of mud up to high-water mark, and in exposed places up to 100 feet or more above high-water mark, lies the zone within which the sea does its work of abrasion. To this zone, even where the breakers are heaviest, a greater extreme vertical range can hardly be assigned than 300 feet, and in most cases it probably falls far short of that extent.

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[1] *Proc. Roy. Soc. Edin.* xvii. (1889), p. 109. See also R. Irvine, *Nature*, 1888, p. 461; J. G. Ross, *ibid.* p. 462. Compare A. Agassiz, *Bull. Mus. Comp. Zool. Harvard*, xvii. No. 3 (1889), p. 125.

[2] T. Stevenson on 'Harbours,' p. 47.

The mechanical work of erosion by the sea is done in six ways.

(i.) The enormous force of the breakers suffices to tear off fragments of the solid rocks.

Abundant examples are furnished by the precipitous shores of Caithness, and of the Orkney and Shetland Islands. It sometimes happens that demonstration of the height to which the effective force of breakers may reach is furnished at lighthouses built on exposed parts of the coast. Thus, at Unst, the most northerly point of Shetland, walls were overthrown and a door was broken open at a height of 196 feet above the sea. At the Bishop Rock lighthouse, on the west of England, a bell weighing 3 cwt. was wrenched off at a level of 100 feet above high-water mark.[2] Some of the most remarkable instances of the power of breakers have been observed by Mr. Stevenson among the islands of the Shetland group. On the Bound Skerry he found that blocks of rock, up to 9½ tons in weight, had been washed together at a height of nearly 60 feet above the sea; that blocks weighing from 6 to 13½ tons had been actually quarried out of their original bed, at a height of from 70 to 75 feet; and that a block of nearly 8 tons had been driven before the waves, at the level of 20 feet above the sea, over very rough ground, to a distance of 73 feet. He likewise records the moving of a 50-ton block by the waves at Barrahead, in the Hebrides.[3] At Plymouth, also, blocks of several tons in weight have been known to be washed about the breakwater like pebbles.[4]

(ii.) The alternate compression and expansion of air in crevices of rocks exposed to heavy breakers dislocates large masses of stone, even above the direct reach of the waves. It is a fact familiar to engineers that, even from a vertical and apparently perfectly solid wall of well-built masonry exposed to heavy seas, stones will sometimes be started out of their places, and that when this happens, a rapid enlargement of the

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[1] T. Stevenson on 'Harbours,' p. 15.

[2] T. Stevenson, *op. cit.* p. 31. D. A. Stevenson, *Min. Proc. Inst. Civ. Engin.* xlvi. (1876), p. 7.

[3] T. Stevenson, *op. cit.* pp. 21-37.

[4] The student will bear in mind that the relative weight of bodies is greatly reduced when in water, and still more in sea-water. The following examples will illustrate this fact (T. Stevenson's 'Harbours,' p. 107)—

—	Specific Gravity.	No. of cubic feet to a ton in air.	No. of feet to a ton in sea-water of specific gravity 1·028.
Basalt	2·99	11·9	18·26
Red granite . .	2·71	13·2	21·30
Sandstone	2·41	14·8	26·00
Cannel Coal . . .	1·54	23·3	70·00

cavity may be effected, as if the walls were breached by a severe bombardment. At the Eddystone lighthouse, during a storm in 1840, a door which had been securely fastened against the force of the surf from without, was actually driven outward by a pressure acting from within the tower, in spite of the strong bolts and hinges, which were broken. We may infer that, by the sudden sinking of a mass of water hurled against the building, a partial vacuum was formed, and that the air inside forced out the door in its efforts to restore the equilibrium.[1] This explanation may partly account for the way in which the stones are started from their places in a solidly built sea-wall. But besides this cause, we must also consider a perhaps still more effective one in the condensation of the air driven before the wave between the joints and crevices of the stones, and its subsequent instantaneous expansion when the wave drops. During gales, when large waves are driven to shore, many tons of water are poured suddenly into a cleft or cavern. These volumes of water, as they rush in, compress the air into every joint and pore of the rock at the further end, and then, quickly retiring, exert such a suction as from time to time to bring down part of the walls or roof. The sea may thus gradually form an inland passage for itself to the surface above, in a "blow-hole," or "puffing-hole," through which spouts of foam and spray are in storms shot high into the air.

On the more exposed portions of the west coast of Ireland, and on the north coast of Cornwall, numerous examples of such blow-holes occur. In Scotland, likewise, they may often be observed, as in the Bullers (boilers) of Buchan on the coast of Aberdeenshire, and the Geary Pot near Arbroath. Magnificent instances occur among the Orkney and Shetland Islands, some of the more shattered rocks of these northern coasts being, as it were, honeycombed by sea-tunnels, many of which open up into the middle of fields or moors.

(iii.) The hydraulic pressure of those portions of large waves that enter fissures and passages tends to force asunder masses of rock. The sea-water which, as part of an inrushing wave, fills the gullies and chinks of the shore-rocks, exerts the same pressure upon the walls between which it is confined as the rest of the wave is doing upon the face of the cliff. Each cleft so circumstanced becomes a kind of hydraulic press, the potency of which is to be measured by the force with which the waves fall upon the rocks outside—a force which often amounts to three tons on the square foot. There can be little doubt that by this means considerable pieces of a cliff are from time to time dislodged.

(iv.) The waves make use of the loose detritus within their reach to break down cliffs exposed to their fury. Probably by far the largest amount of erosion is thus accomplished. The blows dealt against shore-cliffs by boulders, gravel, and sand swung forward by breakers, were aptly compared by Playfair to a kind of artillery.[2] During a storm upon a shingly coast we may hear, at a distance of several miles, the grind of the stones upon each other, as they are dragged back by the recoil of the waves which had launched them forward.[1] In this tear and wear, the loose stones are ground smaller, and acquire the smooth round form so characteristic of a surf-beaten beach. At the same time, they bruise and wear down cliffs against which they are driven. A rock, much jointed, or from any cause presenting less resistance to attack, is excavated into gullies, creeks, and caves; its harder parts standing out as promontories are pierced; gradually a series of detached buttresses and sea-stacks appears as the cliff recedes, and these in turn are wasted until they become mere skerries and sunken surf-beaten reefs (Fig. 167). The surface of the beach is likewise ground down. The reality of this erosion and consequent lowering of level is sometimes instructively displayed where a block of harder rock serves for a time to protect the portion of rocky beach lying beneath it. The block by degrees comes to rest on a growing pedestal, which is eventually cut round by the waves, until the overlying mass, losing its support, rolls down upon the beach. Thereafter the same process is renewed, and the boulder continually diminishes in size (Fig. 168).[2]

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[1] Walker, *Proc. Inst. Civ. Engin.* i. p. 15 ; Stevenson's 'Harbours,' p. 10.

[2] 'Illustrations of the Huttonian Theory,' sec. 97.

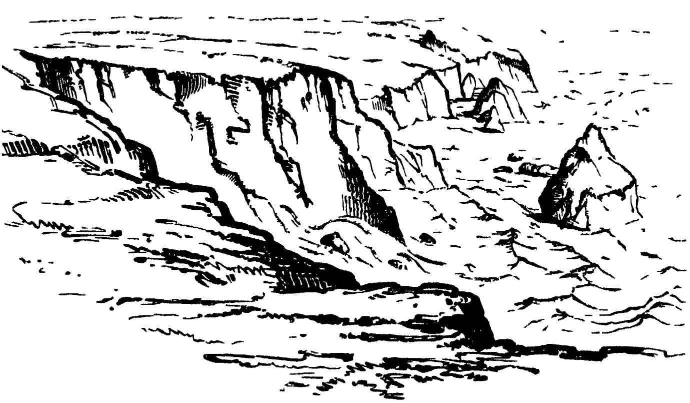

Fig. 167.—Coast of Cornwall, at Bedruthan (Devonian Rocks), cut by the sea into cliffs, bays, and stacks (*B*)

Of the progress of marine erosion, the more exposed parts of the British coast-line furnish many admirable examples. The sea-board of Cornwall presents a most impressive range of cliffs, sea-stacks, caves, gullies, tunnels, reefs, and skerries, showing every stage in the process of demolition (Fig. 167). The west coast of Ireland, exposed to the full swell of the Atlantic, is in innumerable localities completely undermined by caverns, into which the sea enters from both sides. The precipitous coasts of Skye, Sutherland, Caithness, Aberdeen, Kincardine, and Forfar abound in the most impressive lessons of the waste of a rocky sea-margin; while the same picturesque features are prolonged into the Orkney and Shetland Islands, the magnificent cliffs of Hoy towering as a vast wall some 1200 feet above the Atlantic breakers, which are tunnelling and fretting their base.

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[1] For a graphic account of the heavy roll of the boulders and thundering of the billows as heard in a mine under the sea during a storm, see J. W. Henwood, *Trans. Roy. Geol. Soc. Cornwall*, v. p. 11.

[2] See on the action of waves on sea-beaches and sea-bottoms, A. R. Hunt, *Proc. Roy. Dublin Soc.* 1884, p. 241.

If such is the progress of waste where the materials consist of the most solid rocks, we may expect to meet with still more impressive proofs of decay where the coast-line can oppose only soft sand or clay to the march of the breakers. Again, the geological student in Britain can examine for himself many illustrations of this kind of destruction around the shores of these islands. Within the last few hundred years entire parishes, with their farms and villages, have been washed away, and the tide now ebbs and flows over districts which in old times were cultivated fields and cheerful hamlets. The coast of Yorkshire between Flamborough Head and the mouth of the Humber, and also that between the Wash and the mouth of the Thames, suffer at a specially rapid rate, for the cliffs in these parts consist in great measure of soft clay. In some places between Spurn Point and Flamborough Head this loss is said to amount to five yards per annum.[1]

Other parts of the European sea-board likewise furnish instructive lessons as to the progress of marine erosion. The destruction of Heligoland, in the North Sea, has been continuous for centuries, the stages in the disappearance of this island being easily followed on the charts of successive periods.[2] Even the hard crystalline rocks of Scandinavia are unable wholly to withstand the assaults of the Atlantic breakers.[3]

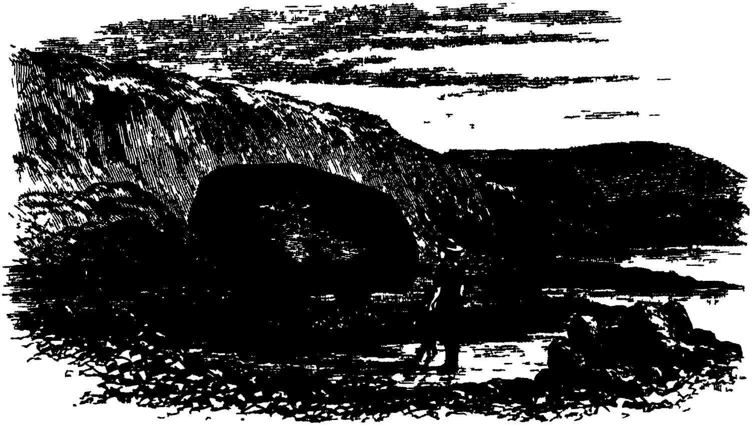

Fig. 108.—Boulder of basalt protecting the portion of beach underneath it, Largo, Fife.

While investigating the progress of waste along a coast-line, the geologist has to consider the varying powers of resistance possessed by rocks, and the extent to which the action of the waves is assisted by that of the subaerial agents. Rocks of little tenacity, and readily susceptible of disintegration, obviously present least resistance to the advance of the waves. A clay, for example, is readily eaten away. If, however, it should contain numerous hard nodules or imbedded boulders, these, as they drop out, may accumulate in front beneath the cliff, and serve as a partial breakwater against the waves (Fig. 169). On the other hand, a hard band or boss of rock may withstand the destruction which overtakes the softer or more jointed surrounding portions, and may consequently be left projecting into the sea, as a line of headland or promontory, or rising as an isolated stack (Fig. 167). But, besides mere hardness or softness, the geological structure of the rocks powerfully influences the nature and rate of the encroachment of the sea Where, owing to the inclination of bedding, joints, or other divisional planes, sheets of rock slope down into the water, they serve as a kind of natural breakwater, up and down which the surges rise and fall during calms, or rush in crested billows during gales, the abrasion being here reduced to the smallest proportions. In no part of the degradation of the land can the dominant influence of rock-structure be more conspicuously observed and instructively studied than along marine cliffs. Where the lines of precipice are abrupt, with numerous projecting and retiring vertical walls, it will almost invariably be found that these perpendicular faces have been cut open along lines of intersecting joint. The existence of such lines of division permits a steep or vertical front to be presented by the land to the sea, because, as slice after slice is removed, each freshly bared surface is still defined by a joint-plane (see p. 524).

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[1] R. Pickwell, *Proc. Inst. Civ. Engin.* li. p. 191. On the waste of the coast between the Thames and Wash, see J. B. Redman, *op. cit.* xxiii. (1864), p. 186; C. Reid, *Geol. Mag.* 2nd dec. iv. p. 136. 'Geology of Holderness,' *Mem. Geol. Surv.* 1885. The Reports of the British Association Committee on the erosion of the sea-coasts of England, 1885-86, give much interesting information on this subject.

[2] K. W. M. Wiebel's 'Die Insel Helgoland,' 4to, Hamburg, 1848.

[3] H. Reusch, *Neues Jahrb.* 1879, p. 244.

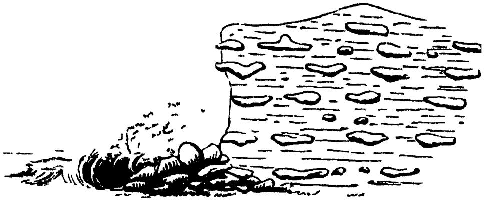

Fig. 169. Cliffs of clay full of septarian nodules, the accumulation of which serves to arrest the progress of the waves

During the study of any rocky coast where these features are exhibited, the observer will soon perceive that the encroachment of the sea upon the land is not due merely to the action of the waves, but that, even on shores where the gales are fiercest and the breakers most vigorous, the demolition of the cliffs depends largely upon the sapping influence of rain, springs, frosts, and general atmospheric disintegration. In Fig. 170, for example, which gives a view of a portion of the northern Caithness coast, exposed to the full fury of the gales and rapid tidal currents which rush from the Atlantic through the Pentland Firth, we see at once that though the base of the cliff is scooped out by the restless surge into long twilight caves, nevertheless the recession of the precipice is caused by the wedging off of slice after slice, along lines of vertical joint, and that this process begins at the top, where the subaerial forces and not the waves are the sculptors. Undoubtedly the sea plays its part by removing the materials dislodged, and preventing them from accumulating against and protecting the face of the precipice. But were it not for the potent influence of subaerial decay, the progress of the sea would be comparatively feeble. The very blocks of stone which give the waves so much of their efficacy as abrading agents, are in great measure furnished to them by the action of the meteoric agents. If sea-cliffs were mainly due to the destructive effects of the waves, they ought to overhang their base, for only at or near their base does the sea act (Fig. 171). But the fact that, in the vast majority of cases, sea-cliffs, instead of overhanging, slope backward, at a greater or less angle, from the sea (Fig. 167), shows that the waste from subaerial action is really greater than that from

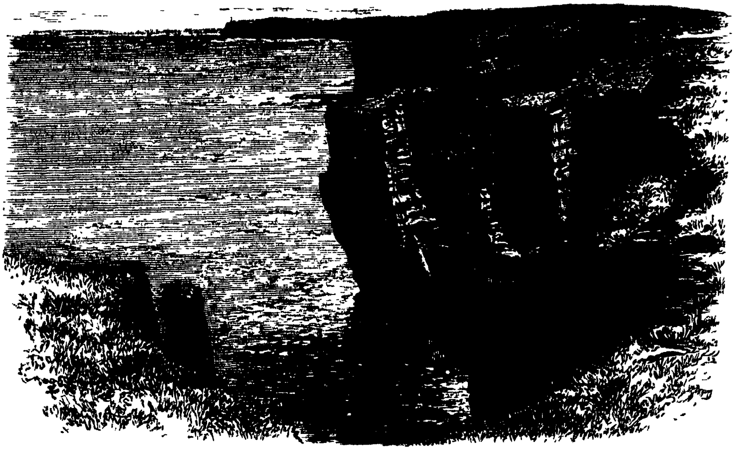

Fig. 170.—Vertical sea-cliffs of flagstone, near Holburn Head, Caithness.

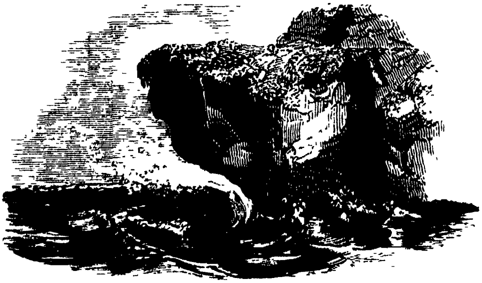

Fig. 171.—Marine erosion, where exceptionally the base of a cliff recedes faster than the upper part.

the action of the breakers.[1] Even when a cliff actually overhangs, however, it may often be shown that the apparent greater recession of its base, and inferentially the more powerful denuding action of the sea, are deceptive. In Fig. 172, one of innumerable examples from the Old Red Sandstone cliffs of Caithness and the Orkney and Shetland Islands, we at once perceive that the process of demolition is precisely similar to that already cited in Fig. 170. The cliff recedes by the loss of successive slices from its sea-front, which are wedged off not by the waves below, but by the subaerial agents above, along lines of parallel joint. To the inclination of these divisional planes at a high angle from the sea, the precipice owes its slope towards the land.

(v.) *Tidal Erosion.*—Reference has already been made (pp. 436, 438) to existence of currents at considerable depths in the ocean, though not in the profounder abysses. These movements have been observed in straits between islands or submarine ridges, and they are doubtless connected with the tidal wave. They seem to possess sufficient scour to prevent the accumulation of sediment, but whether they are effective in eroding hollows on the sea-floor, as has been claimed for them, may be doubted. Their power to dig out hollows or to deepen and widen channels must depend not merely on their velocity but upon the presence of detritus which they can use in abrasion, for without this detritus they could not remove the surface of hard rocks.[2]

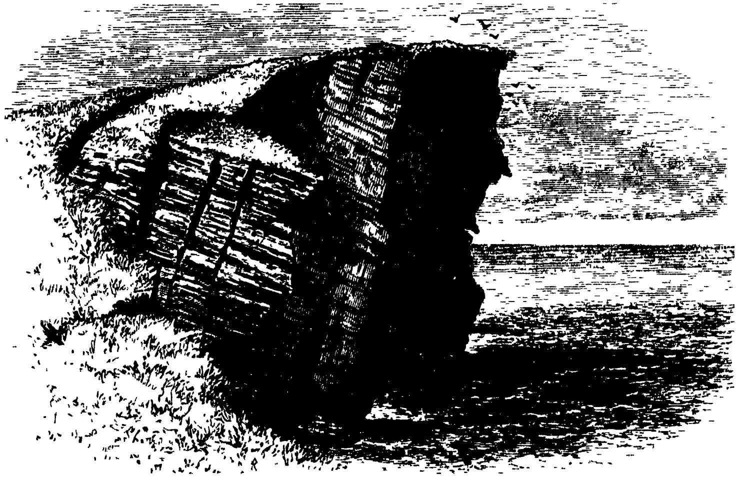

Fig. 172.—Overhanging cliff, Brough of Birsa, Orkney, due to landward inclination of joints.

(vi.) *Ice-Erosion.*—Among the erosive operations of the sea, must be included what is performed by floating ice. Along the margin of Arctic lands, a good deal of work is done by the broken-up floe-ice and ice-foot, both in abrasion and in deposit. Cakes of ice, driven ashore by storms, tear up and redistribute the soft shallow-water or littoral deposits, rub and scratch the rocks, and push gravel and blocks of rock before them as they strand on the beach. Icebergs also, when they get aground in deep water, must greatly disturb the sediment accumulating there, and may grind down any submarine rock on which they grate as they are driven along. The geological operations of floating ice were formerly invoked by geologists to explain much that is now believed to have been entirely the work of ice on land.[1]

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[1] Whitaker, *Geol. Mag.* iv. p. 447.

[2] The potency of tidal action has long been maintained by Mr. T. Mellard Reade, *Proc Geol. Soc. Liverpool*, 1873 ; *Phil. Mag.* xxv. (1888), p. 338.

(3) Transport.—By means of its currents, the sea transports mechanically-suspended sediment to varying distances from the land. The distance will depend on the size, form, and specific gravity of the sediment on the one hand, and on the velocity and transporting power of the marine current on the other. Babbage estimated that if, from the mouth of a river 100 feet deep, suspended limestone mud, of different degrees of fineness, were discharged into a sea having a uniform depth of 1000 feet over a great extent, four varieties of silt, falling respectively through 10, 8, 5, and 4 feet of water per hour, would be distributed as in the following table:[2]—

No.	Velocity of fall per hour.	Nearest distance of deposit to river.	Length of deposit.	Greatest distance of deposit from river.
	feet.	miles.	miles.	miles.
1.	10	180	20	200
2.	8	225	25	250
3.	5	360	40	400
4.	4	450	50	500

It must be borne in mind, however, that mechanical sediment sinks faster in salt than in fresh water.[3] The chief part of the fine mud in the layer of river water, which floats for a time on the salter and heavier sea-water, sinks to the bottom as soon as the two waters commingle. It has been ascertained, nevertheless, by direct observation that an appreciable amount of extremely fine clay is present in ocean-water even far away from land, the proportion so transported depending not only on the size and weight of the particles, but on the temperature and to a less extent on the salinity, being greater the lower the temperature and salinity. In specimens of surface-water taken from various oceans the amount of mechanically suspended silicates (clay) was found to be as follows[4]:—

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[1] For an account of the work of floating ice ("pan-ice") see H. Y. Hind, *Canadian Naturalist*, viii. (1878), p. 229.

[2] *Q. J. Geol. Soc.* xii. 368.

[3] See *ante*, pp. 381, 398 and authorities there cited.

[4] Murray and Irvine, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 243. These authors regard the silica thus mechanically suspended in sea-water as the probable source of most of this substance secreted by marine plants and animals.

	In 14 litres of water.		Per cubic mile of water.
Atlantic Ocean, lat. 51° 20′, long. 31° W.	0·0052 grm.	=	1604 tons
German Ocean, 30 miles E. of May Island	0·0063 ,,	=	1946 ,,
Mediterranean, centre of Eastern basin .	0·0065 ,,	=	2031 ,,
Baltic Sea, salinity 1005·5 . . .	0·0105 ,,	=	3200 ,,
Red Sea, off Brothers Island . . .	0·0006 ,,	=	264 ,,
Indian Ocean, lat. 15° 46′ N., long. 58° 51′ E.	0·0006 ,,	=	264 ,,

Near the land, where the movements of the water are active, much coarse detritus is transported along shore or swept further out to sea. A prevalent wind, by creating a current in a given direction, or a strong tidal current setting along a coast-line, will cause the shingle to travel coastwise, the stones getting more and more rounded and reduced in size as they recede from their source. The Chesil Bank, which runs as a natural breakwater 16 miles long, connecting the Isle of Portland with the mainland of Dorsetshire, consists of drifted rounded shingle.[1] On the Moray Firth, the reefs of quartz-rock about Cullen furnish abundance of shingle, which, urged by successive easterly gales, moves westwards along the coast for more than 15 miles. The coarser sediment probably seldom goes much beyond the littoral zone. Returning to the subject of the depth to which wave-action extends (*ante*, p. 438) we may take note that it has been observed by the fishermen at Land's End that their lobster-pots are often filled with coarse sand and shingle in depths up to 30 fathoms during heavy ground-swells, and that some of the stones weigh as much as one pound.[2] From a depth of even 600 fathoms in the North Atlantic, between the Faroe Islands and Scotland, small pebbles of volcanic and other rocks are dredged up which may have been carried by an Arctic under-current from the north. Mr. Murray and Captain Tizzard, however, have brought up large blocks of rounded shingle from that bank at a depth of 300 fathoms. Such detritus can hardly be due to any present action of the sea, for at these depths the force of currents at the bottom is probably too feeble to push along coarse shingle. It may be moraine-stuff dating back to the ice-sheets of the Glacial Period, its finer particles having been swept away while it is prevented from being buried under submarine mud by the scour of the currents over the bank. Blocks of stone brought up from depths of more than 2000 fathoms in the Atlantic (Lat. 49°N., Long. 43°–44°W.) have probably been dropped by icebergs from the north.[3]

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[1] On the Chesil Bank, see J. Coode, *Min. Proc. Inst. Civ. Engin.* xii. p. 520. J. B Redman, *op. cit.* xi. p. 201 ; xxiii. p. 226 ; *Nature*, xxvi. pp. 30, 104, 150 ; J. Prestwich, *Min. Proc. Inst. Civ. Engin.* xl. p. 115 ; H. W. Bristow and W. Whitaker, *Geol. Mag.* vi. (1869), p. 433 ; O. Fisher, *op. cit.* 1874, p. 285 ; G. H. Kinahan, *op. cit.* 1874. A. R. Hunt, *Proc. Roy. Dublin Soc.* iv. (1884), p. 241. The general transport of littoral detritus in the English Channel is from west to east ; Prof. Prestwich, however, thinks that at the Chesil Bank this direction is locally reversed.

[2] J. N. Douglas, *Min. Proc. Inst. Civ. Engin.* xl. (1875), p. 103.

[3] See charts of part of North Atlantic by Messrs. Siemens Brothers & Co., London, 1882. Some specimens shown to me by Messrs. Siemens are pieces of basalt which may have come from Greenland.

Much fine sediment is visibly carried in suspension by the sea for long distances from land. The Amazon pours so much silt into the sea as to discolour it for several hundred miles. After wet weather, the sea around the shores of the British Islands is sometimes made turbid by the quantity of mud washed by rain and streams from the land. Dr. Carpenter found the bottom-waters of the Mediterranean to be everywhere permeated by an extremely fine mud, derived no doubt from the rivers and shores of that sea. He remarks that the characteristic blueness of the Mediterranean, like that of the Lake of Geneva, may be due to the diffusion of exceedingly minute sedimentary particles through the water.

The great oceanic currents are probably powerful agents in the transport of fine detritus and of living and dead organisms. Coral-reefs appear to flourish best where these currents bring a continuous and abundant supply of food to the reef-builders. The reefs, in turn, furnish an enormous quantity of fine silt, produced by the pounding action of breakers upon them. Before the silt can sink to the bottom, it may be transported to vast distances. The lower portion of the Gulf Stream, from its exit in the Florida Channel northward to Cape Hatteras, a distance of 700 miles, has been compared to a huge muddy river, carrying its silt to the steep slope south of that cape, and depositing here and there patches of green sand along the sides of its course, while the upper waters remain perfectly clear and of the deepest blue. The silt is partly derived from the abrasion of coral-reefs, partly from the decay of the abundant pelagic fauna swept onward by the current. Professor A. Agassiz has recently called attention to the important part which the great oceanic currents, in ancient as in modern times, may have played in the accumulation of limestones, not only by transporting calcareous organisms, but by bringing an abundant food-supply and thereby nourishing a prolific fauna along their track.[1]

During the voyage of the *Challenger*, from the abysses of the Pacific Ocean, at remote distances from land, the dredge brought up bushels of rounded pieces of pumice of all sizes up to blocks a foot in diameter. These fragments were all evidently waterworn, as if derived from land, though we are still ignorant of the extent to which they may have been supplied by submarine volcanic eruptions. Some small pieces were taken on the surface of the ocean in the tow-net. Round volcanic islands, and off the coasts of volcanic tracts of the mainland, the sea is sometimes covered with floating pieces of water-worn pumice swept out by flooded rivers. These fragments may drift away for hundreds or even thousands of miles until, becoming water-logged, they sink to the bottom. The universal distribution of pumice was one of the most noticeable features in the dredgings of the *Challenger*. The clay which is found on the bottom of the ocean, at the greatest distances from any shore, contains only volcanic minerals, and appears to be due to the trituration of volcanic detritus. In approaching the continents, at a distance of several hundred miles from shore, traces of the minerals of the crystalline rocks of the land begin to make their appearance.[2]

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[1] *Amer. Acad.* xi. (1882), p. 126.

[2] Murray, *Proc. Roy. Soc. Edin.* 1876-7, p. 247.

Another not unimportant process of marine transport is that performed by floating ice. Among the Arctic glaciers, moraine stuff is not abundant; but occasional blocks of rock and heaps of earth and stones fall from the cliffs which rise above the general waste of snow. Hence, on the icebergs that float off from these glaciers, rock débris may sometimes be observed. It is transported southwards for hundreds of miles until, by the shifting or melting of the bergs, it is dropped into deep water. The floor of certain portions of the North Atlantic in the pathway of the bergs may be plentifully strewn with this kind of detritus. By means of the ice-foot also, an enormous quantity of earth and stones is every year borne away from the shore on the disrupted ice, and is strewn over the floor of the sounds, bays, and channels.

(4) Reproduction.—The sea, being the receptacle for the material worn away from the land, must receive and store up in its depths all that vast amount of detritus by the removal of which the level and contours of the land are in the course of time so greatly changed. The deposits which take place within the area covered by the sea may be divided into two groups—the inorganic and organic. It is the former with which we have at present to deal; the latter will be discussed with the other geological functions of plants and animals (see pp. 477, 481, *seq.*) The inorganic deposits of the sea-floor are (i.) chemical and (ii.) mechanical.

(i.) Of Chemical deposits now forming on the sea-floor we know as yet very little. At the mouth of the Rhone a crystalline calcareous deposit accumulates, in which the débris of the sea-floor is enveloped. Bischof estimated that no precipitation of carbonate of lime could take place from sea-water until after $\frac{17}{18}$ of the water had evaporated.[1] No deposit of lime in the open sea is possible from concentration of sea-water. But the calcareous formation on the sea-bottom opposite rivers like the Rhone, if not the result of the precipitation of lime by plants or animals, may perhaps be explained by supposing that as the layer of river-water floats and thins out over the surface of the sea in warm weather with rapid evaporation, its comparatively large proportion of carbonate of lime may be partially precipitated. It has been observed near Nice, as well as on the African coasts and other parts of the Mediterranean shores, that on shore-rocks within reach of the water a hard varnish-like crust is deposited. This substance consists essentially of carbonate of lime. As it extends over rocks of the most various composition, it has been regarded as a deposit of lime held in solution in the shore sea-water, and rapidly evaporated in pools or while bathing the surface of rocks exposed to strong sun-heat.[2] But it may possibly be due to organic agency like the amorphous crust of limestone formed by nullipores (see *postea*, p. 477). During the researches of the *Challenger* expedition, important facts in the history of marine chemistry have been obtained from the abysses of the Atlantic and Pacific oceans (see pp. 455, 457, 495).

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[1] 'Chem. Geol.' i. p. 178.

[2] *Bull. Soc. Géol. France* (3), ii. p. 219, iii. p. 46, vi. p. 84. See *postea*, p. 492, where the evaporation in the coral-seas is referred to.

(ii.) The **Mechanical** deposits of the sea may be grouped into subdivisions according as they are directly connected with the waste of the land, or have originated at great depths and remote from land, when their source is not so obvious.[1]

A. *Land-derived or Terrigenous.*—These may be conveniently grouped according to their relative places on the sea-bed.[2]

a. Shore Deposits.—The most conspicuous and familiar are the layers of gravel and sand which accumulate between tide-marks. As a rule, *the coarse materials are thrown up about the upper limit of the beach. They seem to remain stationary there; but if watched and examined* from time to time, they will be found to be continually shifted by high tides and storms, so that though the bank or bar of shingle retains its place, its component pebbles are being constantly moved. During gales coincident with high tides, coarse gravel may be piled up considerably above the ordinary limit of the waves in the form of what are termed *storm-beaches.*[3] Below the limit of coarse shingle upon the beach lies the zone of fine gravel, and then that of sand, the sediment, though liable to irregular distribution, yet tending to arrange itself according to coarseness and specific gravity, the rougher and heavier detritus lying at the upper, and the finer and lighter towards the lower edge of the shore. The nature of the littoral accumulations on any given part of a coast-line must depend either upon the character of the shore-rocks which at that locality are broken up by the waves, or upon the set of the shore-currents, and the kind of detritus they bear with them. Coasts exposed to heavy surf, especially where of a rocky character, are apt to present beaches of coarse shingle between their projecting promontories. Sheltered bays, on the other hand, where wave-action is comparatively feeble, afford a gathering ground for finer sediment, such as sand and mud. Estuaries and inlets, into which rivers enter, frequently show wide muddy flats at low water (p. 398). Deposits of comminuted shells, coral-sand, or calcareous organic remains thrown up on shore, may be cemented into compact rock by the solution and redeposit of carbonate of lime (p. 492). Where tidal currents sweep along a coast yielding much detritus, long bars or shoals may form parallel with the shore. On these the shingle and sand are driven coastwise in the direction of the prevalent current.[4] They not infrequently accumulate as long barriers completely protecting the shores from which they are separated by a channel or lagoon of fresh or brackish water (p. 399). Into this lagoon sediment is washed from the land and aquatic vegetation takes root there, until not infrequently a salt marsh or swamp is formed. Extensive accumulations of this kind are to be found along the eastern coast of the United States.[1]

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[1] See on this subject an important memoir by Messrs. Murray and Renard, *Proc. Roy. Soc. Edin.* 1884, and *Nature*, xxx. (1884); also Murray, *Proc. Roy. Soc.* 1876; *Proc. Roy. Soc. Edin.* ix.; Murray and Renard, *Brit. Assoc.* 1879, sects. p. 340; also for the North Atlantic, 'Den Norske Nordhavs-Expedition,' part ix. (on Oceanic Deposits), 1882. J. Y. Buchanan, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 131. But the chief source of information is now the great Memoir on 'Deep Sea Deposits' by Messrs. Murray and Renard in the Reports of the *Challenger* Expedition, 1891.

[2] On this subject consult the 'Deep-Sea Deposits' of the *Challenger* Report, chap. v.

[3] See Kinahan on Sea-beaches, *Proc. Roy. Irish Acad.* (2nd ser.), iii. p. 101.

[4] See the authorities cited on p. 451, regarding the Chesil Bank.

Among the deposits cast ashore by the sea, not the least interesting are the masses of driftwood which, carried down by rivers are borne by marine currents, sometimes for hundreds of miles, and thrown down in huge accumulations in protected bays. It is in the Arctic seas that this phenomenon obtains its greatest development. Prodigious quantities of terrestrial vegetation are swept by the Siberian rivers into these waters and are carried westwards until stranded in sheltered bays of the coast and of the islands. Every shoal-coast of Spitzbergen presents examples of these heaps of driftwood.[2]

β. Infra-Littoral and Deeper-Water Deposits.—These extend from below low-water mark to a depth of sometimes as much as 2000 fathoms, and reach a distance from land varying up to 200 miles or even more. Near land, and in comparatively shallow water, they consist of banks or sheets of sand, more rarely mixed with gravel. The bottom of the North Sea, for example, which between Britain and the continent of Europe lies at a depth never reaching 100 fathoms, is irregularly marked by long ridges of sand, enclosing here and there hollows where mud has been deposited. In the English Channel, large banks of gravel extend through the Straits of Dover as far as the entrance to the North Sea.[3] These features seem to indicate the line of the chief mud-bearing streams from the land, and the general disposition of currents and eddies in the sea which covers that region, the gravel ridges marking the tracts or junctions of the more rapidly moving currents, while the muddy hollows point to the eddies where the fine sediment is permitted to settle on the bottom. The more prominent features on the floor of the North Sea, however, are probably of much older date than the deposits now accumulating there. Some of them are doubtless relics of the time when the floor of that sea was a broad terrestrial plain. The Dogger Bank, for instance, is probably a prolongation of the Jurassic escarpment of the Yorkshire coast. Other minor submarine features may be partly due to irregular deposition of glacial drift.

During the course of the voyage of the *Challenger*, the approach to land could always be foretold from the character of the bottom, even at distances of 150 and 200 miles. The deposits were found to consist of blue and green muds derived from the degradation of older crystalline rocks. The blue or dark slate-coloured mud takes its colour from decomposing organic matter and sulphide of iron, frequently giving off the odour of sulphuretted hydrogen, and assuming a brown or red hue at the surface, owing to oxidation. Besides occurring in deposits of deep water, iron disulphide is met with on some coasts, cementing sand, gravel, and shells into a coherent mass.[1] The chemical changes that result in the elimination of sulphides from sea-water may be explained by supposing that the decomposing animal and vegetable matter of the sea-floor reduces the sulphates to sulphides, which in turn react on the iron and manganese minerals (principally silicates) in the mud, forming sulphides of those metals. Subsequently the oxygen of the water converts the sulphides to oxides, which gather into concretionary forms.[2] The green muds found at depths of 100 to 700 fathoms are characterised by the presence of a considerable quantity of glauconite grains, either isolated or united into concretions, and frequently filling the chambers of *Foraminifera* or other organisms. Round volcanic islands, the bottom is covered with grey volcanic mud and sand derived from the degradation of volcanic rocks. These deposits can be traced to great distances; from Hawaii they extend for 200 miles or more. Pieces of pumice, scoriæ, &c., occur in them, mingled with marine organisms, and more particularly with abundant grains, incrustations, and nodules of an earthy peroxide of manganese (Fig. 175). Near coral-reefs the sea-floor is covered with a white calcareous mud derived from the abrasion of coral, and frequently containing 95 per cent of carbonate of lime. Beyond a depth of 1000 fathoms, coral mud gives place to a Globigerina ooze or red clay. The east coast of South America supplies a peculiar red mud which is spread over the Atlantic slope down to depths of more than 2000 fathoms.

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[1] N. S. Shaler on sea-coast swamps, *6th Ann. Rep. U. S. Geol. Surv.* 1884-85, p. 353. F. J. H. Merill on barrier beaches of Atlantic coast, *Popular Science Monthly*, Oct. 1890.

[2] Nordenskiöld's '*Vega* Expedition.' Petermann, *Geograph. Mittheil. Ergänzungsheft*, No. 16, where a map of these accumulations on the Arctic coasts is given.

[3] For information as to the English Channel and other parts of the British seas, see J. T. Harrison, *Min. Proc. Inst. Civ. Engin.* vii. (1848), p. 327 (where a map of the submarine deposits will be found); R. A. C. Godwin-Austen, *Quart. Journ. Geol. Soc.* vi. (1849), p. 69—a paper of singular interest and importance; Lebour, *Proc. Geol. Assoc.* iv. p. 158; John Murray, *Min. Proc. Inst. Civ. Engin.* xx. (1860-1), where a map of the North Sea floor is given.

Throughout these land-derived sediments are found minute particles of recognisable minerals. Of these, quartz, often in rounded grains, plays the chief part. Next come mica, felspar, augite, hornblende, and other less abundant constituents of terrestrial rocks, the materials becoming coarser towards land. Occasional pieces of wood, portions of fruits, and leaves of trees in the same deposits further indicate the reality of the transport of material from the land. Shells of pteropods, larval gasteropods, and lamellibranchs are tolerably abundant in these muds, with many infra-littoral species of *Foraminifera*, and diatoms. Below 1500 or

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[1] H. Reusch, *Neues Jahrb.* 1879, p. 255.

[2] J. Y. Buchanan, *Brit. Assoc.* 1881, p. 584. Mr. Buchanan, in renewing this investigation and obtaining many illustrations from the seas around Scotland, has shown that the mud on many parts of the sea-bottom is being continually passed and repassed through the bodies of animals which live upon it. The mineral matter is thus brought in contact with the organic secretions of the animals and is ground up with these in their milling organs. The reducing action of the secretions produces, Mr. Buchanan believes, sulphides from the sulphates of sea-water, and these sulphides, acting on the ochreous matter of the bottom, give rise to sulphides of iron and manganese, which being very unstable in presence of water and oxygen are, where they lie on the surface, soon transformed into oxides. *Proc. Roy. Soc. Edin.* xviii. (1890), p. 17, 'On the occurrence of sulphur in marine muds.' Another view of the decomposition of the sulphates of sea-water is proposed by Dr. Murray and Mr. Irvine. See papers quoted on p. 484.

1700 fathoms, pteropod shells seldom appear, while at 3000 fathoms hardly a foraminifer or any calcareous organism remains.[1]

In some regions vast quantities of terrestrial vegetation are strewn over the sea-bottom, even at depths of 2000 fathoms, and at distances of several hundred miles from land. This fact has been observed by Professor Agassiz off Central America, both in the Atlantic and Pacific Oceans, hardly a single haul of the dredge failing to bring up much vegetable matter, and frequently logs, branches, twigs, seeds, leaves, and fruits.[2]

B. *Abysmal* or *Pelagic.*[3]—Passing over at present the organic deposits which form so characteristic a feature on the floor of the deeper and more open parts of the ocean, we come to certain red and grey clays found at depths of more than 2000 fathoms, down to the bottoms of the deepest abysses. These, by far the most widespread of oceanic deposits,[4] consist of exceedingly fine clay, coloured sometimes red by iron-oxide, sometimes of a chocolate tint from manganese oxide, with grains of augite, felspar, and other volcanic minerals, pieces of palagonite and pumice, nodules of peroxide of manganese, and other mineral substances, together with *Foraminifera*, and in some regions a large proportion of siliceous *Radiolaria.* These clays result from the decomposition of pumice and fine volcanic dust, transported from volcanic islands into mid-ocean, or from the accumulation of the detritus of submarine eruptions. The extreme slowness of deposit is strikingly brought out in the tracts of sea-floor furthest removed from land. From these localities great numbers of sharks' teeth, with ear-bones and other bones of whales, were dredged up in the *Challenger* expedition,—some of them quite fresh, others partially crusted with peroxide of manganese, and some wholly and thickly surrounded with that substance. We cannot suppose that sharks and whales so abounded in the sea at one time as to cover the floor of the ocean with a continuous stratum of their remains. No doubt each haul of the dredge, which brought up so many bones, represented the droppings of many generations. The successive stages of manganese incrustation point to a long, slow, undisturbed period, when so little sediment accumulated that the bones dropped at the beginning remained at the end still uncovered, or only so slightly covered as to be easily scraped up by the dredge. In these deposits, moreover, occur numerous minute spherular particles of metallic iron and "chondres," or spherical internally radiated particles referred to bronzite, which are in all probability of cosmic origin—portions of the dust of meteorites which in the course of ages have fallen upon the sea-bottom (Figs. 173, 174). Such particles, no doubt, fall all over the ocean; but it is only on those parts of the bottom which, by reason of their distance from any land, receive accessions of deposit with extreme slowness—and where therefore the present surface may contain the dust of a long succession of years—that it may be expected to be possible to detect them.[1]

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[1] See papers by Messrs. Murray and Renard, quoted on p. 454, and vol. of *Challenger* Report on 'Deep-Sea Deposits,' p. 190.

[2] 'Three Cruises of the Blake,' and *Bull. Mus. Comp. Zool.* xxiii. No. 1 (1892), p. 11

[3] For information regarding the fauna and deposits of the ocean-abysses, besides the works quoted on page 454, note 1, consult the various writings of Prof. A. Agassiz, especially his 'Three Cruises of the Blake,' and papers in *Bull. Mus. Comp. Zool.* xxi. No. 4, and xxxiii. No. 1; also Haeckel's 'Plankton-Studien,' 1890.

[4] They are estimated to cover upwards of 50,000,000 square miles of the sea-floor. Murray and Irvine, *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

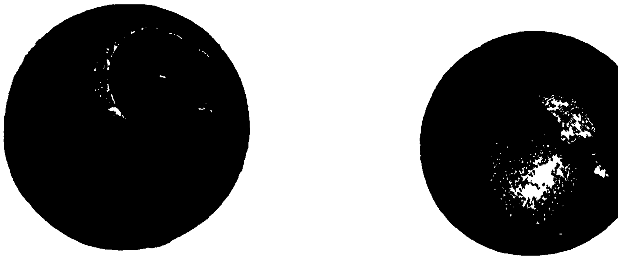

Fig. 173.—Magnetic Spherules (Cosmic Dust) of the ocean-bottom. (Murray and Renard).

a, Black spherule with metallic centre (magnified 60 diameters) from a depth of 2375 fathoms in South Pacific. This represents the common form of these particles, and shows the usual depression on one part of the surface. There is a lustrous crust of magnetite outside.

b, Similar spherule (60 diam.) from which the crust of magnetic oxide has been broken off to show the inner metallic nucleus, here represented by the central lighter part. 3150 fathoms, in the Atlantic.

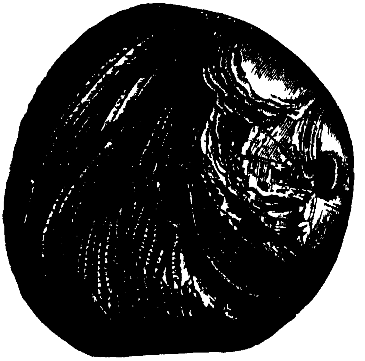

Fig. 174.—Chondre (Cosmic Dust) of the ocean-bottom. (Murray and Renard.)

Spherule of bronzite (mag. 25 diam.) showing the aspect of the chondres found in the abysmal deposits. From a depth of 3500 fathoms, Pacific.

The abundant deposit of peroxide of manganese over the floor of the deep sea is one of the most singular features of recent discovery. It occurs as an earthy incrustation round bits of pumice, bones, and other objects (Fig. 175). The nodules possess a concentric arrangement of lines not unlike those of urinary calculi. That they are formed on the spot, and not drifted from a distance, was made abundantly clear from their containing abysmal organisms, and enclosing more or less of the surrounding bottom, whatever its nature might happen to be. More recently Mr. J. Y. Buchanan dredged similar small manganese concretions from some of the deeper parts of Loch Fyne,[2] and subsequently Dr. John Murray found them abundantly at 10 fathoms in the Firth of Clyde. The formation of such concretions may be analogous to the solution and deposition of oxides of iron and manganese by organic acids, as on lake-floors, bogs, &c. (p. 483).[1] In connection with the chemical reactions indicated by these nodules as taking place on the sea-bottom, reference may be made to a still more remarkable discovery made by Messrs. Murray and Renard in the course of their examinations of the materials brought up from the same abysmal deposits. Minute crystals, simple, twinned, or in spheroidal groups, which occur abundantly in the typical red clay of the central Pacific, have been identified with the zeolite known as christianite. These crystals have certainly been formed directly on the sea-bottom, for they are found gathered round abysmal organisms, and their production has been effected at about the temperature of 32° Fahr. The importance of this fact in reference to the chemistry of marine deposits is at once obvious.

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[1] Murray and Renard on Cosmic Dust, *Proc. Roy. Soc. Edin.* 1884; *Nature*, xxix. *Challenger* Expedition Report, vol. on 'Deep-Sea Deposits,' p. 327 *et seq.*

[2] *Nature*, xviii. (1878), p. 628. *Brit. Assoc.* 1881, p. 583. *Proc. Roy. Soc. Edin.* ix. p. 287. *Trans. R. S. Edin.* xxxvi. (1891), 459. Dieulafait, *Comptes rend.* 1884, p. 589.

From a comparison of the results of the dredgings made in recent years in all parts of the oceans, it is impossible to resist the conclusion that there is little in the character of the deep-sea deposits which finds a parallel among the marine geological formations visible to us on land. It is only among the comparatively shallow-water accumulations of the existing sea that we encounter obvious analogies to the older formations. And thus we reach, by another and a new approach, the conclusion which on other and very different grounds has been arrived at, viz., that the present continental axes have existed from the remotest times, and that the marine strata which constitute so large a portion of their

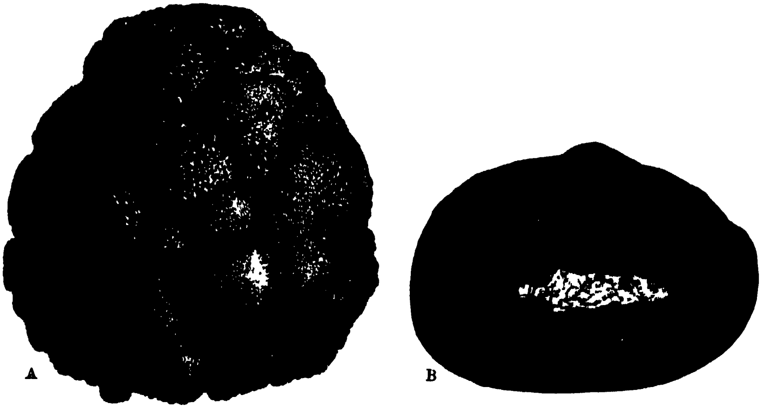

Fig. 175.—Manganese Nodules; floor of the North Pacific. Two-thirds natural size.[2]
A, Nodule from 2900 fathoms showing external form. B, Section of nodule from 2740 fathoms, showing internal concentric deposit round a fragment of pumice.

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[1] Different views have been expressed by Dr. John Murray and Mr. J. Y. Buchanan as to the mode of origin of the marine manganese deposits. See R. Irvine and J. Gibson, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 54.

[2] These and Fig. 174 are taken from plate xxxiii. of the vol. on 'Deep-Sea Deposits' in the Reports of the *Challenger* Expedition. The detailed investigation by Messrs. Murray and Renard of the deep-sea deposits obtained by this expedition forms the most important contribution yet made to our knowledge of the oceanic abysses.

present mass have been accumulated not as deep-water deposits, but in comparatively shallow water along their flanks or over their submerged ridges.[1]

§ 7. DENUDATION AND DEPOSITION.—The results of the action of Air and Water upon Land.[2]

It may be of advantage, before passing from the subject of the geological work of water, to consider the broad results achieved by the co-operation of all the forces by which the surface of the land is worn down. These results naturally group themselves under the two heads of Denudation and Deposition.

1. *Subaerial Denudation—the general lowering of land.*

The true measure of denudation is to be sought in the amount of mineral matter removed from the surface of the land and carried into the sea. This is an appreciable and measurable quantity. There may be room for discussion as to the way in which the waste is to be apportioned to the different forces that have produced it, but the total amount of sea-borne detritus must be accepted as a fact about which, when properly verified, no further question can possibly arise. In this manner the subject is at once disencumbered of difficulty in fixing the relative importance of rain, rivers, frost, glaciers, &c., considered as denuding agents. We have simply to deal with the sum-total of results achieved by all these forces acting severally and conjointly. Thus considered, this subject casts a new light on the origin of existing land-surfaces, and affords some fresh data for approximating to a measure of past geological time.

Of the mineral substances received by the sea from the land, by much the larger portion is brought down by streams; a relatively small amount is washed off by the waves of the sea itself. It is the former, or stream-borne part, which is at present to be considered. The quantity of mineral matter carried every year into the ocean by the rivers of a continent represents the amount by which the general surface of that continent is annually lowered. Much has been written of the vastness of the yearly tribute of silt borne to the ocean by such streams as the Ganges and Mississippi; but "the mere consideration of the number of cubic feet of detritus annually removed from any tract of land by its rivers does not produce so striking an impression upon the mind as the statement of how much the mean surface-level of the district in question would be reduced by such a removal."[1] This method of inquiry is so obvious and instructive that it probably received attention from early geologists, though data were still wanting for its proper application. Playfair, for instance, in speaking of the transference of material from the surface of the land to the bottom of the sea, remarks that "the time requisite for taking away by waste and erosion 2 feet from the surface of all our continents and depositing it at the bottom of the sea cannot be reckoned less than two hundred years."[2] This estimate does not appear to have been based on any actual measurements, and must greatly exceed the truth; but it serves to indicate how broad was the view that Playfair held of the theory which he undertook to illustrate. The first geologist who appears to have attempted to form any estimate on this subject from actually ascertained data, was Mr. Alfred Tylor, who in the year 1850 published a paper in which he estimated the probable amount of solid matter annually brought into the ocean by rivers and other agents. He inferred that the quantity of detritus now distributed over the sea-bottom every year would, at the end of 10,000 years, cause an elevation of the ocean-level to the extent of at least 3 inches.[3] The subject was afterwards taken up by Dr. Croll, who specially drew attention to the Mississippi as a measure of denudation and thereby of geological time.[4]

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[1] *Proc. Roy. Geograph. Soc.* July 1879.

[2] This section is mainly taken from an essay by the author, *Trans. Geol. Soc. Glasgow*, iii. p. 153. The subject has been discussed anew on the basis of more exact knowledge of the interior of the continents and the depths of the sea by Dr. John Murray, *Scottish Geograph. Mag.* 1887. See also a note by Mr. C. Davison, *Geol. Mag.* 1889, p. 409. A. De Lapparent, *Bull. Soc. Géol. France*, xviii. (1890), p. 351.

When the annual discharge of mineral matter carried seaward by a river, and the area of country drained by that river, are both known, the one sum divided by the other gives the amount by which the drainage-area has its mean general level reduced in one year. For it is clear that if a river carries so many millions of cubic feet of sediment every year into the sea, the area drained by it must have lost that quantity of solid material, and if we could restore the sediment so as to spread it over the basin, the layer so laid down would represent the fraction of a foot by which the surface of the basin had been lowered during a year.

It has been already shown that the material removed from the land by streams is twofold—one portion is chemically dissolved, the other is mechanically suspended in the water or pushed along the bottom. Properly to estimate the loss sustained by the surface of a drainage-basin, we ought to know the amount of mineral matter removed in each of these conditions, and also the volume of water discharged, from measurements and estimates made at different seasons and extending over a succession of years. These data have not yet been fully collected from any river, though some of them have been ascertained with approximate accuracy, as in the Mississippi Survey of Messrs. Humphreys and Abbot, and the Danube Survey of the International Commission. As a rule, more attention has been shown to the amount of mechanically suspended matter than to that of the other ingredients. It will be borne in mind, therefore, that the following estimates, in so far as they are based upon only one portion of the waste of the land —that carried in mechanical suspension,—are understatements of the truth.[1]

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[1] Tylor, *Phil. Mag.* 4th series, v. p. 268, 1850.

[2] 'Illustrations,' p. 424. Manfredi had previously made a calculation of the amount of rain that falls over the globe, and of the quantity of earthy matter carried into the sea by rivers. He estimated that this earthy matter distributed over the sea-bed must raise the level of the latter five inches in 348 years. Von Hoff, 'Veranderungen der Erdoberflache,' Band i. p. 232. See the other authorities there cited.

[3] *Phil. Mag. loc. cit.*

[4] *Phil. Mag.* for February 1867 and May 1868; and his 'Climate and Time.' See also *Geol. Mag.* June 1868; *Trans. Geol. Soc. Glasgow*, iii. p. 153

The proportion of mineral substances held in suspension in the water of rivers has been already (p. 379) discussed. It is most advantageous to determine the amount of mineral matter by weight, and then from its average specific gravity to estimate its bulk as an ingredient in river-water. The proportion by weight is probably, on an average, about half that by bulk.

It may seem superfluous to insist that the earthy matter borne into the sea from any given area represents so much actual loss from the surface of that area. Yet this self-evident statement is probably not realised by many geologists to the extent which it deserves. If a stream removes in one year one million of cubic yards of earth from its drainage-basin, that basin must have lost one million of cubic yards from its surface. From the data and authorities which have already been adduced (p. 383), the subjoined table has been constructed, in which are given the results of the measurement of the proportion of sediment in a few rivers. The last column shows the fraction of a foot of rock (reckoning the specific gravity of the silt at 1·9 and that of rock at 2·5) which each river must remove from the general surface of its drainage-basin in one year.

Name of River.	Area of basin in square miles.	Annual discharge of sediment in cubic feet.	Fraction of foot of rock by which the area of drainage is lowered in one year.
Mississippi . .	1,147,000	7,468,694,400	$\frac{1}{6000}$
Ganges (Upper) .	143,000	6,368,077,440	$\frac{1}{823}$
Hoang Ho . .	700,000	17,520,000,000(?)	$\frac{1}{1464}$
Rhone . . .	25,000	600,381,800	$\frac{1}{1528}$
Danube . .	234,000	1,253,738,600	$\frac{1}{6846}$
Po . .	30,000	1,510,137,000	$\frac{1}{729}$

At the present rate of erosion, the rivers named in this table remove one foot of rock from the general surface of their basins in the following ratio:—The Mississippi removes one foot in 6000 years; the Ganges above Ghazipûr does the same in 823 years;[1] the Hoang Ho in 1464 years; the Rhone in 1528 years; the Danube in 6846 years; the Po in 729 years. If these rates should continue, the Mississippi basin will be lowered 10 feet in 60,000 years, 100 feet in 600,000 years, 1000 feet in 6,000,000. Assuming Humboldt's estimate of the mean height of the North American continent, 748 feet,[2] we find that at the Mississippi's rate of denudation, this continent would be worn away in about four and a half million years. The Ganges works still more rapidly. It removes one foot of rock in 823 years, and if Humboldt's estimate of the average height of the Asiatic continent be accepted, viz., 1132 English feet, that mass of land, worn down at the rate at which the Ganges destroys it, would be reduced to the sea-level in little more than 930,000 years. Still more remarkable is the extent to which the River Po denudes its area of drainage. Even though measurements had not been made of the ratio of sediment contained in its water, we should be prepared to find that proportion a remarkably large one, if we look at the enormous changes which, within historic times, have been made by the alluvial accumulations of this river (p. 395). If the Po removes one foot of rock from its drainage basin in 729 years, it will lower that basin 10 feet in 7290 years, 100 feet in 72,900 years. If the whole of Europe (taken at a mean height of 671 feet) were denuded at the same rate, it would be levelled in rather less than half a million of years.

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[1] Geologists are largely indebted to Mr. Mellard Reade for the attention which he has given to the important part played by chemical solution in the general denudation of the land. From the data collected by him he infers, as the proportion of solids in solution in the water of the Mississippi is $\frac{1}{5816}$ by weight, about 150 millions of tons of dissolved mineral must be carried by this river annually into the sea. In the River Plate the proportion is $\frac{1}{6149}$, in the St. Lawrence $\frac{1}{6240}$, in the Amazon $\frac{1}{10800}$. Presidential Address, *Liverpool Geol. Soc.* 1884.

It is not pretended that these results are strictly accurate. On the other hand, they are not mere guesses. The amount of water flowing into the sea, and the annual discharge of sediment, have been in each case measured with greater or less precision. The areas of drainage may perhaps require to be increased or lessened. But though some change may be made upon the ultimate results just given, it is hardly possible to consider them attentively without being forced to ask whether those enormous periods which geologists have been in the habit of demanding for the accomplishment of geological phenomena, and more especially for the very phenomena of denudation, are not in reality far too vast. If the Mississippi is carrying on the process of denudation so rapidly that at the same rate the whole of North America might be levelled in four and a half millions of years, surely it is most unphilosophical to demand unlimited ages for similar but often much less extensive denudations in the geological past. Moreover, that rate of erosion appears, on the whole, to be rather below the average in point of rapidity. The Po, for instance, works more than eight times as fast. But as the physics of the Mississippi have been more carefully studied than those of perhaps any other river, and as that river drains so extensive a region, embracing so many varieties of climate, rock, and soil, we shall probably not exaggerate the result if we assume the Mississippi ratio as an average. It is, of course, obvious that as the level of the land is lowered, the rate of subaerial denudation decreases, so that on the supposition that no subterranean movements took place to aid or retard the denudation, the last stages in the demolition of a continent must be enormously slower than during earlier periods.

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[1] In my original paper the area of drainage of the Ganges was given as 432,480 square miles. But the area from which the annual discharge of silt was there given was only that part of the Gangetic basin above Ghazipûr, which Dr. Haughton estimates at 143,000 square miles (*Proc. Roy. Dublin Soc.* 1879, No. xxxix.) Hence, as he has pointed out, the rate of erosion is really much greater than I had made it. I have recalculated the rate from the altered data, and the result is as given above.

[2] *Ante*, pp. 39, 40, where other and more probable estimates of the height of the land are given. But as the numbers do not affect the argument, those originally assumed are here retained.

It must not be forgotten, however, that as already remarked, the estimates here given, inasmuch as they are based only on the material removed in mechanical suspension, are probably understatements of the truth. If we take into account also the material carried away in chemical solution, the rate of subaerial denudation will be considerably heightened. It is difficult, however, to apportion the loss of dissolved substance from the surface of the land. The salts contained in solution in river-water are derived not only from the superficial rocks, but probably to a much greater extent from springs which sometimes carry up dissolved substances from considerable depths. In the end, no doubt, as the level of the land is reduced by subaerial waste, this subterranean solution will tell, but it can hardly be said sensibly to affect the lowering of the level from century to century. Mr. Mellard Reade, from his researches into this subject, believes that the amount of solids in solution is on the whole about one-third of that of those in suspension. He finds this to be the ratio in the Nile, the Danube, and the Mississippi, the last-named being in many respects a typical river. If, as he proposes, we add this additional loss by chemical solution to the amount of material removed in mechanical suspension from the Mississippi basin, the annual lowering of the level of the basin will be raised from $\frac{1}{6000}$ to $\frac{1}{4500}$ of a foot.[1] It is quite true that the loss of mineral matter from the whole basin would be equivalent to that sum, but there would obviously not be strictly a lowering of the level of the basin to that amount. It is difficult to see how we are to discriminate between superficial and subterranean solution; and until some separation of this kind is made, it seems hardly legitimate to class the whole of the dissolved matter with that carried in mechanical suspension as a measure of the annual loss from the surface of the land.

There is another point of view from which a geologist may advantageously contemplate the active denudation of a country. He may estimate the annual rainfall and the proportion of water which returns to the sea. If he can obtain a probable average ratio for the earthy substances contained in the river-water which enters the sea, he will be able to estimate the mean amount of loss sustained by the whole country. Thus, taking the average rainfall of the British Islands at 36 inches annually, and the superficial area over which this rain is discharged at 120,000 square miles, then it will be found that the total quantity of rain received in one year by the British Isles is equal to about 68 cubic miles of water. If the proportion of rainfall returned to the sea by streams be taken at a third, there are 23 cubic miles; if at a fourth, there are 17 cubic miles of fresh water sent off the surface of the British Islands into the sea in one year. Assuming, in the next place, that the average ratio of mechanical impurities is only $\frac{1}{5000}$ by volume of the water, the proportion of the rainfall returned to the sea being $\frac{1}{4}$, then it will follow that $\frac{1}{8800}$ of a foot of rock is removed from the general surface of Britain every year. One foot will be planed away in 8800 years. If the mean height of the British Islands be taken at 650 feet, then, if the ratio now assumed were to continue, these islands might be levelled in about five and a half millions of years. Much more detailed observation is needed before any estimate of this kind can be based upon accurate and reliable data. But it illustrates a method of vividly bringing before the mind the reality and extent of the denudation now in progress.

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[1] T. Mellard Reade, Presidential Address, *Liverpool Geol. Soc.* 1884-85.

2. *Subaerial Denudation—the unequal erosion of land.*

It is obvious that the earthy matter annually removed from the surface of the land does not come equally from the whole surface. The determination of its total quantity furnishes no aid in apportioning the loss, or in ascertaining how much each part of the surface has contributed to the total amount of sediment. On plains, watersheds, and more or less level ground, the proportion of loss may be small, while on slopes and in valleys it may be great, and it may not be easy to fix the true ratios in these cases. But it must be borne in mind that estimates and measurements of the sum-total of denudation are not thereby affected. If we allow too little for the loss from the surface of the table-lands, we increase the proportion of the loss sustained by the sides and bottoms of the valleys, and *vice versâ*.

While these proportions vary indefinitely with the form of the surface, rainfall, &c., the balance of loss must always be, on the whole, on the side of the sloping surfaces. In order to show the full import of this part of the subject, certain ratios may here be assumed which are probably understatements rather than exaggerations. Let us take the proportion between the extent of the plains and table-lands of a country, and the area of its valleys, to be as nine to one; in other words, that, of the whole surface of the country, nine-tenths consists of broad undulating plains, or other comparatively level ground, and one-tenth of steeper slopes. Let it be further assumed that the erosion of the surface is nine times greater over the latter than over the former area, so that while the more level parts of the country have been lowered one foot, the valleys have lost nine feet. If, following the measurements and calculations already given, we admit that the mean annual quantity of detritus carried to the sea may, with some probability, be regarded as equal to the yearly loss of $\frac{1}{6000}$ of a foot of rock from the general surface of the country, then, apportioning this loss over the surface in the ratio just given, we find that it amounts to $\frac{5}{9}$ of a foot from the more level grounds in 6000 years, and 5 feet from the valleys in the same space of time. Now, if $\frac{5}{9}$ of a foot be removed from the level grounds in 6000 years, 1 foot will be removed in 10,800 years; and if 5 feet be worn out of the valleys in 6000 years, 1 foot will be worn out in 1200 years. This is equal to a loss of only $\frac{1}{12}$ of an inch from the table-lands in 75 years, while the same amount is excavated from the valleys in 8½ years.

It may seem at first sight that such a loss as only a single line from the surface of the open country during more than the lapse of a long human life is almost too trifling to be taken into account, as it is certainly too small to be generally appreciable. In the same way, if we are told that the constant wear and tear which is going on before our eyes in valleys and water-courses, does not effect more than the removal of one line of rock in eight and a half years, we may naturally enough regard such a statement as probably an under-estimate. But if we only permit the multiplying power of time to come into play, the full force of those seemingly insignificant quantities is soon made apparent. For we find by a simple piece of arithmetic that, at the rate of denudation which has been just postulated as probably a fair average, a valley of 1000 feet deep may be excavated in 1,200,000 years, a period which, in the eyes of most geologists, will seem short indeed.

Objection may be taken to the ratios from which this average rate of denudation is computed. Without attempting to decide what this average rate actually is—a question which must be determined for each region upon much fuller data than are at present available—the geologist will find advantage in considering, from the point of view now indicated, what, according to the most probable estimates, is actually in progress around him. Let him assume any other apportioning of the total amount of denudation, he does not thereby lessen the measurement of that amount, which can be and has been ascertained in the annual discharge of rivers. A certain determined quantity of rock is annually worn off the surface of the land. If, as already remarked, we represent too large a proportion to be derived from the valleys and water-courses, we diminish the loss from the open country; or, if we make the contingent derived from the latter too great we lessen that from the former. Under any ascertained or assumed proportion, the facts remain, that the land loses a certain ascertainable fraction of a foot from its general surface per annum, and that the loss from the valleys and water-courses is larger than that fraction, while the loss from the level ground is less.

3. *Marine Denudation—its comparative rate.*

From the destructive effects of occasional storms an exaggerated estimate has been formed of the relative potency of marine erosion. That the amount of waste by the sea must be inconceivably less than that effected by the subaerial agents, will be evident if we consider how small is the extent of surface exposed to the power of the waves, when contrasted with that which is under the influence of atmospheric waste. In the general degradation of the land, this is an advantage in favour of the subaerial agents which would not be counterbalanced unless the rate of waste by the sea were many thousands or millions of times greater than that of rains, frosts, and streams. But in reality no such compensation exists. In order to see this, it is only necessary to place side by side measurements of the amount of work actually performed by the two classes of agents. Let us suppose, for instance, that the sea eats away a continent at the rate of ten feet in a century—an estimate which probably attributes to the waves a much higher rate of erosion than can, as the average, be claimed for them.[1] Then a slice of about a mile in breadth will require about 52,800 years for its demolition, ten miles will be eaten away in 528,000 years, one hundred miles in 5,280,000 years. Now we have already seen that, on a moderate computation, the land loses about a foot from its general surface in 6000 years, and that, by the continuance of this rate of subaerial denudation, the continent of Europe might be worn away in about 4,000,000 years. Hence, before the sea, advancing at the rate of ten feet in a century, could pare off more than a mere marginal strip of land, between 70 and 80 miles in breadth, the whole land might be washed into the ocean by atmospheric denudation.

Some such results as these would necessarily be produced if no disturbance took place in the relative levels of sea and land. But in estimating the amount of influence to be attributed to each of the denuding agents in past times, we require to take into account the complicated effects that would arise from the upheaval or depression of the earth's crust. If frequent risings of the land, or elevations of the sea-floor into land, had not taken place in the geological past, there could have been no great thickness of stratified rocks formed, for the first continents must soon have been washed away. But the great depth of the stratified part of the earth's crust, and the abundant breaks and unconformabilities among the sedimentary masses, show how constantly, on the one hand, the waste of the land was compensated by elevatory movements, while, on the other, the continued upward growth of vast masses of sedimentary deposits was rendered possible by prolonged depression of the sea-bed.

When a mass of land is raised to a higher level above the sea, a larger surface is exposed to denudation. As a rule, a greater rainfall is the result, and consequently, also, a more active waste of the surface by subaerial agents. It is true that a greater extent of coast-line is exposed to the action of the waves, but a little reflection will show that this increase will not, on the whole, bring with it a proportionate increase in the amount of marine denudation. For, as the land rises, the cliffs are removed from the reach of the breakers, and a more sloping beach is produced, on which the sea cannot act with the same potency as when it beats against a cliff-line. Moreover, as the sea-floor approaches nearer the surface of the water, it is the former detritus washed off the land, and deposited under the sea, which first comes within the reach of the currents and waves. This serves, in some measure, as a protection to the solid rock below, and must be cut away by the ocean before that rock can be exposed anew. While, therefore, elevatory movements tend on the whole to accelerate the action of subaerial denudation, they in some degree check the natural and ordinary influence of the sea in wasting the land. Again, the influence of movements of depression will probably be found to tend in an opposite direction. The lowering of the general level of the land will, as a rule, help to lessen the rainfall, and consequently the rate of subaerial denudation. At the same time, it will aid the action of the waves, by removing under their level the detritus produced by them and heaped up on the beach, and by thus bringing constantly within reach of the sea fresh portions of the land-surface. But even with these advantages in favour of marine denudation, the balance of power will, on the whole, remain always on the side of the subaerial agents.

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[1] It may be objected that this rate is far below that of parts of the east coast of England (*ante*, p. 446). But along the rocky western coast of Britain the loss is perhaps not so much as one foot in a century.

4. *Marine Denudation—its final result.*

The general result of the erosive action of the sea on the land is the production of a submarine plain. As the sea advances, the sites of successive lines of beach pass under low-water mark. Where erosion is in full operation, the littoral belt, as far down as wave-action has influence, is ground down by moving detritus. This result may often be instructively observed, on a small scale, upon rocky shores where sections like that in Fig. 176 occur. We can conceive that, should no change of level between sea and land take place, the sea might slowly eat its way far into the land, and produce a gently sloping, yet apparently almost horizontal selvage of plain, covered permanently by the waves. In such a submarine plain, the influence of geological structure, and notably of the relative powers of resistance of different rocks, would make itself conspicuous, as may be seen even on a small scale on any rocky beach (Fig. 167). The present promontories caused by the superior hardness of their component rocks would no doubt be represented by ridges on the subaqueous plateau, while the existing bays and creeks, worn out of softer rocks, would be marked by lines of valley or hollow.[1]

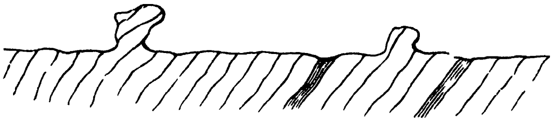

Fig. 176.—Section of rocks ground down to a plain on the beach by wave-action.

This tendency to the formation of a submarine plain along the margin of the land deserves special attention by the student of denudation. The angle at which a mass of land descends to the sea-level serves roughly to indicate the depth of water near shore. A precipitous coast commonly rises out of deep water, a low coast is usually skirted with shallow water, the line of slope above sea level being in a general way prolonged below it. The belt of beach forms a kind of terrace or notch along the maritime slope. Sometimes, where the coast-line is precipitous, this terrace is nearly or wholly wanting. In other places, it runs out a good way beyond low-water mark. On a great scale, the floor of

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[1] Mr. Whitaker, in the excellent paper on subaerial denudation cited on p. 449 has pointed out the different results which are obtained by the subaerial forces from those of sea-action in the production of lines of cliff.

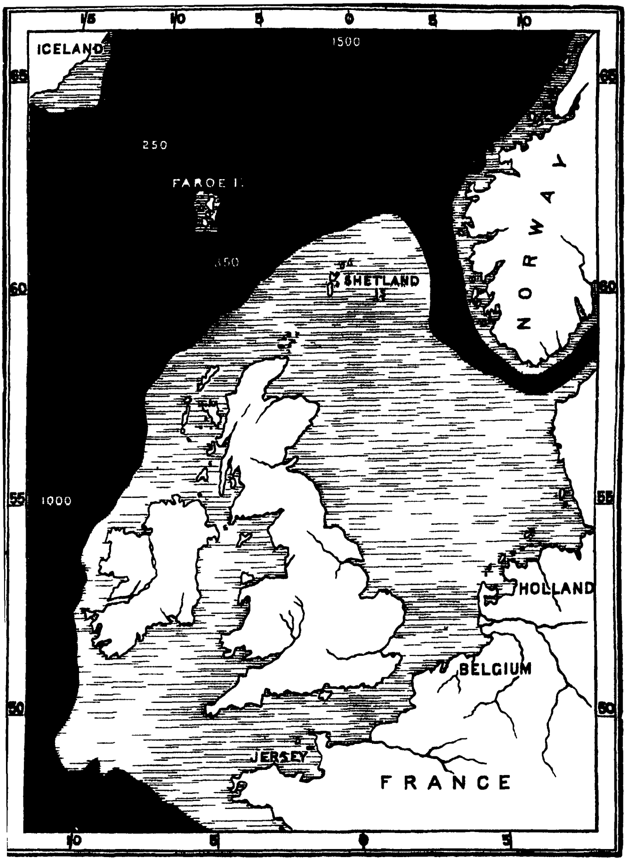

Fig. 177.—Map of British submarine platform.
The darker tint represents sea bottom more than 100 fathoms deep, while the paler shading shows the area of less depths. The figures mark the depth in fathoms. The narrow channel between Norway and Denmark is 2580 feet deep.

the North Sea and that of the Atlantic Ocean, for some distance to the west of Ireland, may be regarded as a marine platform that once formed part of the European continent (Fig. 177), and has been reduced by denudation and subsidence to its present position.

So far as the present régime of nature has been explored, it would seem to be inevitable that, unless where subterranean movements interfere, or where volcanic rocks are poured forth at the surface, a submarine plain should be formed along the margin of the land. This final result of denudation has been achieved again and again in the geological past, as is shown by the existence of table-lands of erosion (*ante*, p. 43). To these table-lands the name of "plains of marine denudation" has been applied by Sir A. C. Ramsay. From what has now been said, however, it will be seen that in their actual production the sea has really had less to do than the meteoric agents. A "plain of marine denudation" is that base-level of erosion to which a mass of land had been reduced mainly by the subaerial forces—the line below which further degradation became impossible, because the land was thereafter protected by being covered by the sea. Undoubtedly the last touches in the long process of sculpturing were given by marine waves and currents, and the surface of the plain, save where it has subsided, may correspond generally with the lower limit of wave-action. Nevertheless, in the past history of our planet, the influence of the ocean has probably been far more conservative than destructive. Beneath the reach of the waves, the surface of the abraded land has escaped the demolition which sooner or later overtakes all that rises above them.

5. *Deposition—the framework of new land.*

If a survey of the geological changes in daily progress upon the surface of the earth leads us to realise how momentously the land is being worn down by the various epigene agents, it ought also to impress us with the vast scale on which new formations—the foundation of future land—are being continually accumulated. Every foot of rock removed from the surface of a country is represented by a corresponding amount of sedimentary material arranged somewhere beneath the sea. Denudation and deposition are synchronous and co-equal.

On land, vast accumulations of detrital origin are now in progress. Alluvial plains of every size, from those of mere brooks up to those of the largest rivers, are built up of gravel, sand, and mud derived from the disintegration of higher ground. From the level of the present streams, successive terraces of these materials can be followed up to heights of several hundred feet. Over wide regions, the daily changes of temperature, moisture and wind supply a continual dust, which, in the course of centuries, has accumulated to a depth of sometimes 1500 feet, and covers thousands of square miles of the surface of the continents. The numerous lakes that dot the surface of the land serve as receptacles in which a ceaseless deposition of sediment takes place. Already an unknown number of once existent lakes has been entirely filled up with detrital accumulations, and every stage towards extinction may be traced in those that remain.

But extensive though the terrestrial sedimentary deposits may be, they can be regarded merely as temporary accumulations of the detritus. Save where protected and concealed under the water of lakes, they are everywhere exposed to a renewal of the denudation to which they owe their origin. Only where the sediment is strewn over the sea-floor beneath the limit of breaker-action, is it permitted to accumulate undisturbed. In these quiet depths, are now growing the shales, sandstones, and limestones, which by future terrestrial revolutions will be raised into land, as those of older times have been. Between the modern deposits and those of former sea-bottoms which have been upheaved, there is the closest parallel. Deposition will obviously continue as long as denudation lasts. The secular movements of the crust seem to have been always sufficiently frequent and extensive to prevent cessation of these operations. And so we may anticipate that it will be for many geological ages yet to come. Elevation of land will repair what has been lost by superficial waste, and subsidence of sea-bottom will provide space for continued growth of sedimentary deposits.

Section iii. Life.

Among the agents by which geological changes are now, and have in past time been effected upon the earth's surface, living organisms take by no means an unimportant place. They serve as a vehicle for continual transferences from the atmosphere into the mineral world, and from the mineral world back into the atmosphere. Thus, they decompose atmospheric carbon-dioxide, and in this process have gradually removed from the atmosphere the vast volumes of carbon now locked up within the earth's crust in beds of solid coal. By their decomposition, organic acids are produced which partly enter into mineral combinations, and partly return to the atmosphere as carbon-dioxide. Plants abstract from the soils silica, alkalies, calcium-phosphate, and other mineral substances, which enter largely into the composition of the hard parts of animals. On the death and decomposition of animals, these substances are once more relegated to the inorganic world, thence to enter upon a new circulation through the tissues of living organisms.

From a geological point of view, the operations of organic life may be considered under three aspects—destructive, conservative, and reproductive.

§ 1. Destructive Action.

Plants in several ways promote the disintegration of rocks.

1. By keeping the surfaces of rocks moist, plants provide means for the continuous solvent action of water. This influence is particularly observable among liverworts, mosses, and similar moisture-loving plants.

2. By their decay, plants supply an important series of organic acids, which exert a powerful influence upon soils, minerals, and rocks. The humus, or organic portion of vegetable soil, consists of the remains of plants and animals in all stages of decay, and contains a complex series of organic compounds still imperfectly understood. Among these are humic, ulmic, crenic and apocrenic acids.[1] The action of these organic acids is twofold. (1) From their tendency to oxidation, they exert a markedly reducing influence (*ante*, pp. 343, 360, 456). Thus they convert metallic

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[1] See J. Roth, 'Allgemeine und Chemische Geologie,' 1883, p. 596.

sulphates into sulphides, as in the blue marine muds, and the abundant pyritous incrustations of coal-seams, shell-bearing clays, and even sometimes of mine-timbers. Metallic salts are still further reduced to the state of native metals. Native silver occurs among silver ores in fossil wood among the Permian rocks of Hesse. Native copper has been frequently noticed in the timber-props of mines; it was found hanging in stalactites from the timbers of the Ducktown copper mines, Tennessee, when the mines were re-opened after being shut up during the civil war. Fossil fishes from the Kupferschiefer have been incrusted with native copper, and fish-teeth have been obtained from Liguria completely replaced by this metal. (2) They exert a remarkable power of dissolving mineral substances.[1] This phase of their activity has probably been undervalued by geologists.[2] Experiments have shown that many of the common minerals of rocks are attacked by organic acids. There is reason to believe that in the decomposition effected by meteoric waters, and usually attributed mainly to the operation of carbonic acid, the initial stages of attack are due to the powerful solvent capacities of the humus acids. Owing, however, to the facility with which these acids pass into higher states of oxidation, it is chiefly as carbonates that the results of their action are carried down into deeper parts of the crust or brought up to the surface. Although carbonic acid is no doubt the final condition into which these unstable organic acids pass, yet during their existence, they attack not merely alkalies and alkaline earths, but even dissolve silica. The relative proportion of silica in river-waters has been referred to the greater or less abundance of humus in their hydrographical basins,[3] the presence of a large percentage of silica being a concomitant of a large proportion of organic matter. Further evidence of the important influence of organic acids upon the solution of silica is supplied by many siliceous deposits (p. 483).

Wherever a layer of humus has spread over the surface of the land, traces of its characteristic decompositions may be found in the soils, subsoils and underlying rocks. Next the surface, the normal colour of the subsoils is usually changed by oxidation and hydration into tints of brown and yellow, the lower limit of the weathered zone being often sharply defined. Where the humus acids can freely attack the hydrated peroxide of iron, they remove it in solution, and the decomposed rock or soil is thereby bleached. This may be observed where pine-trees grow on ferruginous sand, a rootlet one-sixth of an inch in diameter being by its decay capable of whitening the sand to a distance of from one to two inches around it.[1] It has recently been proposed to ascribe mainly to the operation of the humus acids the thick layer of decomposed rock above noticed (p. 350) as observable so frequently south of the limits of the ice of the Glacial Period, and the inference has been drawn that, even where the surface is now comparatively barren, the mere existence of this thick decomposed layer affords a presumption that it once underlay an abundant vegetation, such as a heavy primeval forest-growth.[2] Nor is the chemical action confined to the superficial layers. The organic acids are carried down beneath the surface, and initiate that series of alterations which carbonic acid and the alkaline carbonates effect among subterranean rock masses (*ante*, p. 360).

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[1] Professor Sollas has noticed the formation of minute hemispherical pits on limestone by the solvent action of a lichen, *Verrucaria rupestris* (*Brit. Assoc.* 1880, sects. p. 586). See also J. G. Goodchild, *Geol. Mag.* 1890, p. 464.

[2] This has been strongly insisted upon by A. A. Julien in a memoir on the Geological Action of the Humus Acids. *Amer. Assoc.* 1879, p. 311. Professor H. C. Bolton has experimented on the action of citric acid on 200 different mineral species, and he finds that this organic acid possesses a power of dissolving minerals only slightly less than that of hydrochloric acid: *Brit. Assoc.* 1880, sects. p. 505.

[3] Sterry Hunt's 'Chemical and Geological Essays,' pp. 126-150.

3. Plants insert their roots or branches between the joints of rock, or penetrate beneath the soil. Two marked effects are traceable to this action. In the first place, large slices of rock may be wedged off from the sides of wooded hills or cliffs. Even among old ruins, an occasional sapling ash or elm may be found to have cast its roots round a portion of the masonry, and to be slowly detaching it from the rest of the wall. In the second place, the soil and subsoil are opened up to the decomposing influences of the air and descending water. The distance to which, under favourable circumstances, roots may penetrate downward are much greater than might be supposed. Thus in the loess of Nebraska the buffalo-berry (*Shepherdia argophylla*) has been observed to send a root 55 feet down from the surface, and in that of Iowa the roots of grasses penetrate from 5 to 25 feet.[3]

4. By attracting rain, as thick forests, woods, and mosses, more particularly on elevated ground, are believed to do, plants accelerate the general scouring of a country by running water. The indiscriminate destruction of the woods in the Levant has been assigned, with much plausibility, as the main cause of the present desiccation of that region.[4]

5. Plants promote the decay of diseased and dead plants and animals, as when fungi overspread a damp rotting tree or the carcase of a dead animal.

Animals.—The destructive influences of the animal kingdom likewise show themselves in several distinct ways.

1. The surface-soil is moved, and exposed thereby to attack by rain, wind, &c. As Darwin showed, the common earth-worm is continually engaged in bringing up the fine particles of soil to the surface. He found that in fifteen years a layer of burnt marl had been buried under 3 inches of loam, which he attributed to this operation.[5] It has been already pointed out that part of the growth of soil may be due to wind-action (*ante*, p. 331). There can be no doubt, however, that the materials of vegetable soil are largely commingled and fertilised by the

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[1] Kindler, *Poggend. Annal.* xxxvii. (1836), p. 203. J. A. Phillips, 'Ore Deposits,' 1884, p. 14.

[2] Julien, *Amer. Assoc.* 1879, p. 378.

[3] Aughey's 'Physical Geography and Geology of Nebraska,' 1880, p. 275.

[4] See on this disputed question the works cited by Rolleston, *Journ. Roy. Geog. Soc.* xlix. (1879). The destruction of forests is also alleged to increase the number and severity of hail-storms.

[5] *Trans. Geol. Soc.* v. p. 505. 'Vegetable Mould,' 1881.

earth-worm, and in particular that, by being brought up to the surface, the fine particles are exposed to meteoric influences, notably to wind and rain. Even a grass-covered surface may thus suffer slow denudation. Lob-worms on sandy shores possibly aid transport by waves and tides, inasmuch as they bring up large quantities of fresh sand.[1]

Burrowing animals, by throwing up the soil and subsoil, expose these to be dried and blown away by the wind. At the same time, their subterranean passages serve to drain off the superficial water, and to injure the stability of the surface of the ground above them. In Britain, the mole and rabbit are familiar examples. In North America, the prairie dog and gopher have undermined extensive tracts of pasture-land in the west. In Cape Colony, wide areas of open country seem to be in a constant state of eruption from the burrowing operations of multitudes of *Bathyergi* and *Chrysochloris*—small mole-like animals which bring up the soil and bury the grassy vegetation under it. The decomposition of animal remains produces chemical changes similar to those resulting from the decay of plants.

2. The flow of streams is sometimes interfered with, or even diverted, by the operations of animals. Thus the beaver, by cutting down trees (sometimes 1 foot or more in diameter) and constructing dams with the stems and branches, checks the flow of water-courses, intercepts floating materials, and sometimes even diverts the water into new channels. This action is typically displayed in Canada and in the Rocky Mountain regions of the United States. Thousand of acres in many valleys have been converted into lakes, which, intercepting the sediment carried down by the streams, and being likewise invaded by marshy vegetation, have subsequently become morass and finally meadow-land. The extent to which, in these regions, the alluvial formations of valleys have been modified and extended by the operations of the beaver, is almost incredible. The embankments of the Mississippi are sometimes weakened to such an extent by the burrowings of the cray-fish as to give way, and allow the river to inundate the surrounding country. Similar results have happened in Europe from the subterranean operations of rats.

3. Some mollusks (*Pholas*, *Saxicava*, *Teredo*, &c., Fig. 178) bore into stone or wood, and by the number of contiguous perforations greatly weaken the materials. Pieces of drift-wood are soon riddled with long holes by the teredo; while wooden piers, and the bottoms of wooden ships, are often rapidly perforated. Saxicavous shells, by piercing stone and leaving open cavities for rain and sea-water to fill, promote its decay. A potent cause of the destruction of coral-reefs is to be found in the borings of mollusks, annelids, and echino-

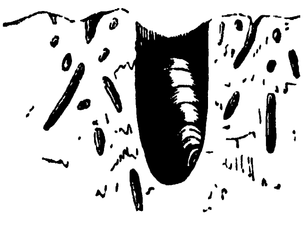

Fig. 178.—Shell-borings in limestone.

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[1] Mr. Davison estimates the amount to be sometimes nearly 2000 tons annually over an acre. *Geol. Mag.* 1891.

derms, whereby masses of coral are weakened so as to be more easily removed by breakers.

4. Many animals exercise a ruinously destructive influence upon vegetation. Of the various insect-plagues of this kind it will be enough to enumerate the locust, phylloxera, and Colorado beetle. The pasture in some parts of the south of Scotland has in recent years been much damaged by mice, which have increased in numbers owing to the indiscriminate shooting and trapping of owls, hawks, and other predaceous creatures. Grasshoppers cause the destruction of vegetation in some parts of Wyoming and other Western Territories of the United States. The way in which animals destroy each other, often on a great scale, may likewise be included among the geological operations now under description. As an illustration of this action, reference may be made to the occasionally enormous development of the protozoon genera *Peridinium* and *Glenodinium*, and the consequent killing off of the oysters and other mollusks in the waters of Port Jackson.[1]

§ 2. Conservative Action.

Plants.—The protective influence of vegetation is well known.

1. The formation of a stratum of turf protects soil and rocks from being rapidly removed by rain or wind. Hence the surface of a district so protected is denuded with extreme slowness, except along the lines of its water-courses. A crust of lichens doubtless on the whole protects the rock underneath it from atmospheric agents.[2]

2. Many plants, even without forming a layer of turf, serve by their roots or branches to protect the loose sand or soil on which they grow from being removed by wind. The common sand-carex and other arenaceous plants bind littoral sand-dunes, and give them a permanence which would at once be destroyed were the sand laid bare again to the storms. In North America, the sandy tracts of the Western Territories are in many places protected by the sage-brush and grease-wood. The growth of shrubs and brushwood along the course of a stream not only keeps the alluvial banks from being so easily undermined and removed as would otherwise be the case, but serves to arrest the sediment in floods, filtering the water, and thereby adding to the height of the flood-plain. On some parts of the west coast of France, extensive ranges of sand-hills have been planted with pine woods, which, while preventing the destructive inland march of the sand, also yield a large revenue in timber, and have so influenced the

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[1] An occurrence of this kind in March 1891 led to an almost complete destruction of the oysters, mussels, and other bivalves; the rest of the littoral fauna—limpets and other univalves, starfish, worms, ascidians, and other lower forms of life—were so seriously affected that dead and dying were strewn about in great numbers, while the higher forms, able to move rapidly, had retired to deep water. T. Whittelegge, *Records of Australian Museum*, i. No. 9 (1891), p. 179.

[2] But see the remark already made, *ante*, p. 472, note 1.

climate as to make these districts a resort for pulmonary invalids.[1] In tropical countries, the mangrove grows along the sea-margin, and not only protects the land, but adds to its breadth, by forming and increasing a maritime alluvial belt.

3. Some marine plants likewise afford protection to shore rocks. This is done by the hard incrustration of calcareous nullipores; likewise by the tangles and smaller fuci which, growing abundantly on the littoral zone, break the force of waves, or diminish the effects of ground-swell.

4. Forests and brushwood protect soil, especially on slopes, from being washed away by rain. This is shown by the disastrous results of the thoughtless destruction of woods. According to Reclus,[2] in the three centuries from 1471 to 1776, the "vigueries," or provostry-districts of the French Alps, lost a third, a half, and even three-fourths of their cultivated ground, and the population has diminished in somewhat similar proportions. From 1836 to 1866 the departments of Hautes and Basses Alpes lost 25,000 inhabitants, or nearly one-tenth of their population—a diminution which has with plausibility been assigned to the reckless removal of the pine forests, whereby the steep mountain sides have been washed bare of their soil. The desiccation of the countries bordering the eastern Mediterranean has been ascribed to a similar cause.[3]

5. In mountain districts, pine-forests exercise also an important conservative function in preventing the formation or arresting the progress of avalanches. In Switzerland, some of the forests which cross the lines of frequent snow-falls are carefully preserved.

Animals do not on the whole exert an important conservative action upon the earth's surface, save in so far as they form new deposits, as will be immediately referred to. On many shores, however, by thickly encrusting rocks, they act like the marine vegetation above alluded to, and protect these to a considerable extent from abrasion by the waves. The most familiar example in Europe of this action is that of the common acorn-shell or barnacle (*Balanus balanoides*). Serpulæ often encrust considerable masses of a coral-reef, and act like nullipores, in protecting decaying and dead corals from being so rapidly broken up by the waves as they would otherwise be. But even soft-bodied animals, such as sponges and ascidians, when they spread over rocks near low-water, afford protection from at least the less violent attacks of the breakers. Professor Herdman, who has called attention to this subject, enumerates as the more important animals in protecting shore rocks: Foraminifera (such as *Planorbulina vulgaris*), calcareous and fibrous sponges, hydroid zoophytes, sea anemones, corals, annelides (serpula), polyzoa, cirripedes, mollusks (such as gregarious forms like the mussel and oyster, and gasteropods like the limpet), and simple and compound ascidians.[1]

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[1] De Lavergne, 'Economie rurale de la France depuis 1789,' p. 297. *Edin. Review*, Oct. 1864, article on Coniferous Trees.

[2] 'La Terre,' p. 410. J. C. Brown, 'Reboisement en France,' London 1876. According to Dr. J. Carret, however, the deterioration of the climate of Savoy and the diminution of the population there cannot be attributed to déboisement. The cutting-down of the forests dates from the First Empire, but replanting has been going on for some time, and the forest area is now a little larger than it was last century. Nevertheless the depopulation of the higher tracts, which had begun before last century, continues, notwithstanding the replanting of the slopes: *Assoc. Française*, 1879, p. 538.

[3] Recent attempts to reclothe the desiccated stone-wastes of Dalmatia with trees have been attended with success. See Mojsisovics, *Jahrb. Geol. Reichsanst.* 1880, p. 210.

In the prairie regions of Wyoming and other tracts of North America, some interesting minor effects are referable to the herds of roving animals which migrate over these territories. The trails made by the bison, the elk, and the big-horn or mountain sheep, are firmly trodden tracks on which vegetation will not grow for many years. All over the region traversed by the bison, numerous circular patches of grass are to be seen which have been formed on the hollows where this animal has wallowed. Originally they are shallow depressions, formed in great numbers where a herd of bisons has rested for a time. On the advent of the rains they become pools of water; thereafter grasses spring up luxuriantly, and so bind the soil together that these grassy patches or "bison-wallows," may actually become slightly raised above the general level, if the surrounding ground becomes parched and degraded by winds.[2]

§ 3. Reproductive Action.

Plants.—Both plants and animals contribute materials towards new geological formations, chiefly by the aggregation of their remains, partly from their chemical action. Their remains are likewise enclosed in deposits of sand and mud, the bulk of which they thus help to increase. Of plant-formations the following illustrative examples may be given:—

1. Sea-weeds.—It was long ago shown by Forchhammer that fucoids abstract an appreciable amount of lime, magnesia, soda, and other components of sea-water, and he believed that these plants probably played an important part in the accumulation of the older Palæozoic sediments.[3] The calcareous nullipores which encrust shore rocks provide solid material which, either growing *in situ* or broken off and distributed by the waves, gives rise to a distinct geological deposit. Considerable masses of a structureless limestone are formed in the Bay of Naples mainly by calcareous algæ. By the infiltration of water into the dead parts of the material the organic structure is destroyed.[4]

2. Humus, Black Soils, &c.—Long-continued growth and decay of vegetation upon a land-surface not only promotes disintegration of the superficial rock, but produces an organic residue, the intermingling of which with mineral débris constitutes vegetable soil. Undisturbed through long ages, this process has, under favourable conditions, given rise to thick accumulations of a rich dark loam. Such are the "regur," or

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[1] *Proc. Liverpool Geol. Soc.* 1884-85.

[2] Comstock, in Captain Jones's 'Reconnaissance of N.W. Wyoming,' 1875, p. 175.

[3] *Brit. Assoc.* 1844, p. 155.

[4] J. Walther, *Zeitsch. Deutsch. Geol. Gesell.* xxxvii. (1885), p. 329.

rich black cotton soil of India, the "tchernayzem," or black earth of Russia, containing from 6 to 10 per cent of organic matter, and the deep fertile soil of the American prairies and savannahs. These formations cover plains many thousands of square miles in extent. The "tundras" of northern latitudes are frozen plains of which the surface is covered with arctic mosses and other plants.[1]

3. Peat-mosses and Bogs.[2]—In temperate and arctic latitudes, marshy vegetation accumulates *in situ* to a depth of sometimes 40 or 50 feet, in what are termed bogs or peat-mosses. In northern Europe and America these vegetable deposits have been largely formed by mosses, especially species of *Sphagnum*, which, growing on hill-tops, slopes, and valley-bottoms as a wet spongy fibrous mass, die in their lower parts and send out new fibres above. Some peaty deposits have been formed in lakes, either by the growth of aquatic plants on the bottom, or by the precipitation of decaying vegetation from the layer of matted plant-growth which creeps from shore along the surface of the water.[3] In some cases, peat may possibly have arisen in brackish-water conditions. There are even instances cited of marine peat formed of sea-weeds (*Zostera, Fucus*, &c.)[4] Among the Alps, as also in the northern parts of South America, and among the Chatham Islands, east of New Zealand, various phanerogamous plants form on the surface a thick stratum of peat.

A succession can sometimes be detected in the vegetation out of which the peat has been formed. Thus in Europe, among the bottom-layers traces of rush (*Juncus*), sedge (*Iris*), and fescue-grass (*Festuca*) may be observed, while not infrequently an underlying layer of fresh-water marl, full of mouldering shells of *Limnea, Planorbis*, and other lacustrine mollusks, shows that the area was originally a lake which has been filled up with vegetation. The next and chief layer of the peat will usually be found to consist mainly of matted fibres of different mosses, particularly *Sphagnum, Polytrichum*, and *Bryum*, mingled with roots of coarse grasses and aquatic plants. The higher layers frequently abound in the remains of heaths. Every stage in the formation of peat may be observed where mosses are cut for fuel; the portions at the bottom are more or less compact, dark brown or black, with comparatively little external appearance of vegetable structure, while those at the top are loose, spongy, and fibrous, where the living and dead parts of the mosses commingle (Fig. 179).

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[1] See a pamphlet, 'Uber den Humus,' by Dr. von Ollech, Berlin, Bodo Grundmann, 1890. It may be well to take note here again of the extensive accumulation of red loam in limestone regions which have long been exposed to atmospheric influences. To what extent vegetation may co-operate in the production of this loam, has not been determined. Fuchs believes that the "terra rossa" is only present in dry climates where the amount of humus is small (*ante*, p. 350, and authorities there cited).

[2] For a general account see T. R. Jones, *Proc. Geol. Assoc.* vi. (1880), p. 207. On the composition, structure, and history of peat-mosses, consult Rennie's 'Essays on Peat-moss,' Edinburgh, 1810; Steele's 'Natural and Agricultural History of Peat-moss,' Edinburgh, 1826; Templeton, *Trans. Geol. Soc.* v. p. 608; H. Schinz-Gessner, 'Der Torf, &c.,' Zurich, 1857; Pokorny, *Verhand. Geol. Reichsanst. Vienna*, 1860; Senft, 'Humus-, Marsch-, Torf-, und Limonit-bildungen,' Leipzig, 1862; G. Thenius, 'Die Torfmoore Oesterreichs,' Vienna, 1874; J. Geikie, *Trans. Roy. Soc. Edin.* xxiv. p. 363. For a list of plants that supply material for the formation of peat, see J. Macculloch's 'Western Islands,' vol. i.; T. R. Jones, above quoted; J. Fruh, "Kritische Beiträge zur Kenntniss des Torfes," *Jahrb. Geol. Reichsanst.* xxxv. (1885), p. 677; and *Bull. Soc. Botan. Suisse*, i. (1891).

[3] For accounts of matted vegetation covering lakes, see *Land and Water*, 1876, pp. 180, 282.

[4] J. Macculloch, 'System of Geology,' 1831, vol. ii. p. 341. Sirodot, *Compt. rend.* lxxxvii. (1878), p. 267. Bobierre, *Ann. Mines*, 7me sér. x. (1876), p. 469.

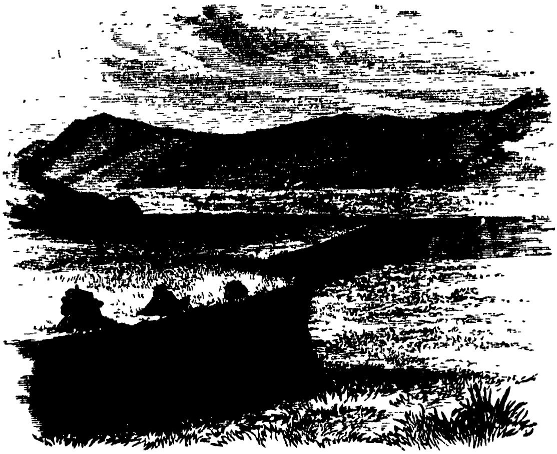

Fig. 179.—View of Scottish Peat-moss opened for digging fuel.

It frequently happens that remains of trees occur in peat-mosses. Sometimes the roots are imbedded in soil underlying the moss, showing that the moss has formed since the growth of the trees (see p. 331). In other cases, the roots and trunks occur in the heart of the peat, proving that the trees grew upon the mossy surface, and were finally, on their decay, enclosed in growing peat (Fig. 180). A succession of trees has been observed among the Danish peat-mosses, the Scotch fir (*Pinus sylvestris*) and white birch (*Betula alba*) being characteristic of the lower layers; higher portions of the peat being marked

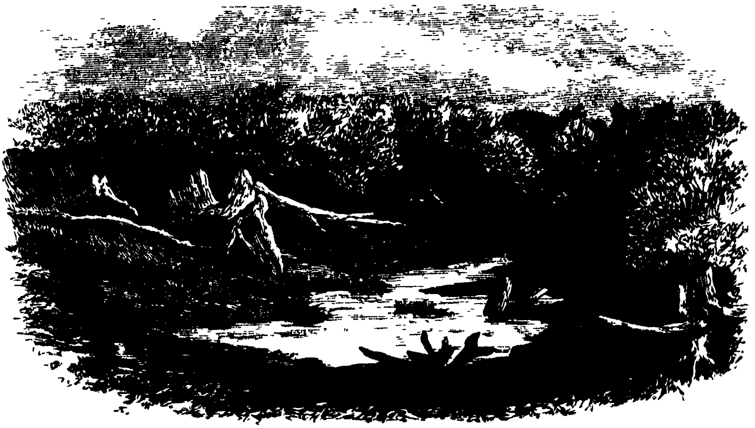

Fig. 180.—Scene in a Sutherland Peat-moss.

by remains of the oak, while at the top comes the common beech. Remains of the same kinds of trees are abundant in the bogs of Scotland and Ireland.

The rate of growth of peat varies within wide limits. An interesting example of the formation and growth of peat-moss in the latter half of the seventeenth century is on record.[1] In the year 1651 an ancient pine-forest occupied a level tract of land among the hills in the west of Ross-shire. The trees were all dead, and in a condition to be blown down by the wind. About fifteen years later every vestige of a tree had disappeared, the site being occupied by a spongy green bog into which a man would sink up to the arm-pits. Before the year 1699 the tract had become firm enough to yield good peat for fuel. In the valley of the Somme, three feet of peat will grow in from 30 to 40 years.[2] On a moor in Hanover, a layer of peat from 4 to 6 feet thick formed in about 30 years. Near the Lake of Constance, a layer of 3 to 4 feet grew in 24 years. Among the Danish mosses, a period of 250 to 300 years has been required to form a layer 10 feet thick. Much must depend upon the climate, slope, drainage, and soil. Some European peat-mosses are probably of extreme antiquity, having begun to form soon after the surface was freed from the snow and ice of the glacial period. In the lower parts of these mosses, traces of the arctic flora which then overspread so much of the continent are to be met with. In other instances, the mosses are at least as late as Roman times.[3] Change of climate and likewise of drainage may stop the formation of peat, so that shrubs and trees spring up on the firm surface. Along the Flemish coast a layer of peat containing mosses, rushes, and other fresh-water plants underlies four or five feet of clays and sands with marine shells, indicating a subsidence and re-elevation of the country.[4]

Peat-mosses cover many thousand square miles of Europe and North America.[5] About one-seventh of Ireland is covered with bogs, that of Allen alone comprising 238,500 acres, with an average depth of 25 feet. Where lakes are gradually converted into bogs, the marshy vegetation advances from the shores, and sometimes forms a matted treacherous green surface, beneath which the waters of the lake still lie. The decayed vegetable matter from the under part of this crust sinks to the bottom of the water, forming there a fine peaty mud, which slowly grows upward. Eventually, as the spongy covering spreads over the lake, a layer of brown muddy water may be left between the still growing vegetation above and the muddy deposit at the bottom. Heavy rains, by augmenting this intermediate watery layer, sometimes make the centre swell up until the matted skin of moss bursts, and a deluge of black mud pours into the surrounding country. The inundated ground is covered permanently with a layer of black peaty earth.

From the treacherous nature of their surface, peat-mosses have frequently been the receptacles for bodies of men and animals that ventured upon them. As peat possesses great antiseptic power, these remains are usually in a state of excellent preservation. In Ireland, the remains of the extinct large Irish elk (*Megaceros hibernicus*) have been dug up from many of the bogs. Human weapons, tools, and ornaments have been exhumed from peat-mosses; likewise crannoges, or pile-dwellings (constructed in the original lakes that preceded the mosses), and canoes hollowed out of single trees.

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[1] Earl of Cromarty, *Phil. Trans.* xxvii.

[2] J. Kolb, *Proc. Inst. Civ. Engin.* xl. (1875), p. 35.

[3] On mosses of Flanders and north of France see H. Debray, *Bull. Soc. Géol. France*, 3me sér. ii. p. 46. *Ann. Soc. Géol. Nord*, 1870-74, p. 19. Lorié, *Arch. Mus. Teyler*, 2me sér. iii. part 5 (1890), pp. 423, 439. Below the moors of Oldenburg, Roman coins, weapons, and plank-roads are found at a depth of 13 feet and upwards (*Petermann's Mittheil.* 1883, v.) On the Bohemian peat-bogs, F. Sitensky, *Archiv Landesdurch-forsch. Böhmen*, vi. (1891); on those lying east of the Christiania Fjord, G. E. Stangeland, 'Torvmyrer,' *Norges Geolog. Undersög.* 1892; on those of Schleswig-Holstein, R v. Fischer-Benzon, *Abh. Naturwiss. Ver.* Hamburg, xi. (1891).

[4] *Ann. Mines*, 7me sér. x. p. 468.

[5] For an account of the fresh-water morasses and swamps of the United States see Shaler, *10th Ann. Rep. U.S. Geol. Surv.* 1890, p. 255.

4. **Mangrove-Swamps.**—On the low moist shores and river-mouths of tropical countries, the mangrove-tree plays an important geological part. It grows in such situations in a dense jungle, sometimes twenty miles broad, which fringes the coast as a green selvage, and runs up, if it does not quite occupy, creeks and inlets. The mangrove flourishes in sea-water, even down to low-water mark, forming there a dense thicket, which, as the trees drop their radicles and take root, grows outward into the sea. It is singular to find terrestrial birds nestling in the branches above, and crabs and barnacles living among the roots below. By this network of subaqueous radicles and roots, the water that flows off the land is filtered of its sediment, which, retained among the vegetation, helps to turn the spongy jungle into a firm soil.[1] On the coast of Florida, the mangrove swamps stretch for long distances, as a belt from five to twenty miles broad, which winds round the creeks and inlets. At Bermuda, the mangroves co-operate with grasses and other plants to choke up the creeks and brackish lakes. In these waters calcareous algæ abound, and, as their remains are thrown up amidst the sand and vegetation, they form a remarkably calcareous soil (pp. 128, 337).[2]

5. **Diatom-Earth or Ooze.**—As the minute siliceous plants called diatoms occur both in fresh and salt water, the deposit formed from their congregated remains is found both on the sites of lakes and on the sea-floor. The most extensive terrestrial accumulations of this nature now in course of formation are probably those of the warm water marshes supplied by the hot springs of the Yellowstone Park, where the oozy deposits and drier meadows cover many square miles, sometimes to a depth of six feet.[3] "Infusorial" earth and "tripoli powder" consist mainly of the frustules and fragmentary débris of diatoms, which have accumulated on the bottoms of lacustrine areas, the purer varieties

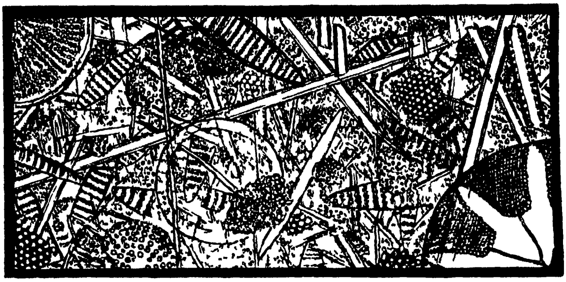

Fig. 181. Diatom ooze dredged up by the *Challenger* Expedition from a depth of 1950 fathoms in the Antarctic Ocean. Lat. 53° 55′ S., Long. 108° 38′ E. Magnified 300 diameters.

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[1] For an account of the growth of mangrove swamps, see N. S. Shaler, *10th Ann. Rep. U. S. Geol. Surv.* 1890, p. 291.

[2] See Nelson, *Q. J. Geol. Soc.* ix. p. 200 *et seq.*; J. J. Rein, *Bericht Senckenb. Naturf. Ges.* 1872-3, p. 139; Wyville Thomson's 'Atlantic,' i. p. 290. (See *ante*, pp. 128, 337.)

[3] W. H. Weed, *Botanical Gazette*, xiv. (1889), p. 117.

containing 90 to 97 per cent of silica. They form beds sometimes upwards of 30 feet thick. (Richmond, Virginia; Bilin, Bohemia; Aberdeenshire.) *Diatomaceæ* occur in abundance, both in the surface-waters of the ocean and on the bottom. In the Arctic Ocean and in the seas around the Shetland Islands living diatoms sometimes form vast floating banks of a yellowish slimy mass, which impedes the prosecution of the herring fishery.[1] The frustules of these plants accumulate at depths of from 1260 to 1975 fathoms, as a pale straw-coloured deposit, which when dried is white and very light (Fig. 181).[2]

6. Chemical Deposits.—But, besides giving rise to new formations by the mere accumulation of their remains, plants do so also both directly and indirectly by originating or precipitating chemical solutions. The most conspicuous example of this action is the production of calc-sinter. Some plants (several species of *Chara*, for instance) have the power of decomposing the carbonic acid dissolved in water, and precipitating calcium-carbonate within their own cell walls. Others (such as the mosses *Hypnum*, *Bryum*, &c.[3]) precipitate the carbonate as an inorganic incrustation outside their own substance. Some observers have even maintained that this is the normal mode of production of calc-sinter in large masses like those of Tivoli. It is certainly remarkable that this substance may be observed encrusting fibrous bunches of moss (*Hypnum*, &c.), when it can be found in no other part of the water-course, and this, too, at a spring containing only 0·034 of carbonate. It is evident that if the deposit of calc-sinter were due to mere evaporation, it would be more or less equally spread along the edges and shallow parts of the channel. It appears to arise first from the decomposition of dissolved carbonic acid by the living plants, and it proceeds along their growing stems and fibres. Subsequently, evaporation and loss of carbon-dioxide cause the carbonate to be precipitated over and through the fibrous sinter, till the substance may become a solid crystalline stone. Varieties of sinter are traceable to original differences in the plants precipitating it. Thus at Weissenbrunnen, near Schalkau, in Central Germany, a cavernous but compact sinter is made by *Hypnum molluscum*, while a loose porous kind gathers upon *Didymodon capillaceus*.[4]

Some marine algæ, as above noticed, abstract calcium-carbonate from sea-water and build it up into their own substance. A nullipore (*Lithothamnium nodosum*) has been found to contain about 84 per cent of calcium-carbonate, 5½ of magnesium-carbonate, with a little phosphoric acid, alumina, and oxides of iron and manganese.[5] Vegetable life has likewise the power of precipitating silica from solution in hot springs and forming siliceous sinter. In the geyser district of the Yellowstone Park it has been ascertained that the extensive sinter deposits are largely formed by vegetation, which causes the siliceous material to be thrown down as a stiff gelatinous substance, in many varied forms. Algæ are chiefly concerned in this process. On the death of the plant the jelly-like mass, which consists of the siliceous filaments of the algæ and their slimy envelope, loses part of its water, becomes cheese-like in consistency, and finally hardens into stone.[1]

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[1] Murray and Irvine, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 231. On the source whence marine plants and animals obtain their silica, see *ante*, p. 450, and *postea*, p. 494.

[2] Messrs. Murray and Irvine estimate the area of sea-bottom covered with diatom ooze at 10,420,600 square miles, and the mean depth of the surface of the deposit at 1477 fathoms below sea-level, *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

[3] Also phanerogams, as *Ranunculus* and *Potamogeton*.

[4] See V. Schauroth, *Z. Deutsch. Geol. Ges.* iii. (1851), p. 137. Cohn, *Neues Jahrb.* 1864, p. 580, gives some interesting information as to the plants by which the sinter is formed, and their work. In Scotland *Hypnum commutatum* is a leading sinter-former.

[5] Gümbel, *Abhandl. Bayerisch. Akad. Wissensch.* xi. 1871.

In the formation of extensive beds of bog-iron-ore, the agency of vegetable life is of prime importance. In marshy flats and shallow lakes, where the organic acids are abundantly supplied by decomposing plants, the salts of iron are attacked and dissolved. Exposure to the air leads to the oxidation of these solutions, and the consequent precipitation of the iron in the form of hydrated ferric oxide, which, mixed with similar combinations of manganese, and also with silica, phosphoric acid, lime, alumina, and magnesia, constitutes the bog-ore so abundant on the lowlands of North Germany and other marshy tracts of northern Europe.[2] On the eastern sea-board of the United States, large tracts of salt marsh, lying behind sand-dunes and bars, form receptacles for much active chemical solution and deposit. There, as in the European bog-iron districts, ferruginous sands and rocks containing iron are bleached by the solvent action of humus acids, and the iron removed in solution is chiefly oxidized and thrown down on the bottom. In presence of the sulphates of sea-water and of organic matter, the iron of ferruginous minerals is partially changed into sulphide, which on oxidation gives rise to the precipitation of bog-iron.[3] The existence of beds of iron-ore among sedimentary formations affords strong presumption of the existence of contemporaneous organic life by which the iron was dissolved and precipitated.

The humus acids, which possess the power of dissolving silica, precipitate it in incrustations and concretions. Julien describes hyalite crusts at the Palisades of the Hudson, due, as he thinks, to the action of the rich humus upon the fallen débris of diabase. The frequent occurrence of nodules of flint and chert in association with organic remains, the common silicification of fossil wood, and similar close relations between silica and organic remains, point to the action of organic acids in the precipitation of this mineral. This action may consist sometimes in the neutralisation, by organic acids, of alkaline solutions charged with silica;[4] sometimes in the solution and re-deposit of colloid silica by albuminoid compounds, developed during the decomposition of organic matter in deposits through which silica has been disseminated, the deposit taking place preferentially round some decaying organism, or in the hollow left by its removal.[1]

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[1] W. H. Weed, *Ninth Ann. Rep. U. S. Geol. Survey*, 1889. *Amer. Journ. Sci.* xxxvii. (1889), p. 351.

[2] Forchhammer, *Neues Jahrb.* 1841, p. 17, *ante*, p. 146.

[3] Julien, *Amer. Assoc.* 1879, p. 347, and *ante*, p. 455.

[4] Leconte, *Amer. Journ. Sci.* 1880, p. 181.

Animals.—Animal formations are chiefly composed of the remains of the lower grades of the animal kingdom, especially of *Mollusca*, *Actinozoa*, and *Foraminifera*.

1. Calcareous.—Lime, chiefly in the form of carbonate, is the mineral substance of which the solid parts of invertebrate animals are mainly built up. The proportion of carbonate of lime in sea-water is so small as to have presented a difficulty in the endeavour to account for the vast quantities of this substance eliminated by marine organisms. Mr. J. Y. Buchanan, however, has suggested that the testaceous denizens of the sea assimilate their lime from the gypsum dissolved in sea-water, forming sulphide in the interior of the animal, which is transformed into carbonate on the outside.[2] Messrs. Murray and Irvine have experimentally proved that sea-animals can secrete carbonate of lime from sea-water from which carbonate of lime is rigidly excluded, and thus that the other lime salts, notably the sulphate, are made use of in the process. They infer that the living tissues of the lower animals and the effete secretions of higher forms, produce carbonate of ammonia, which in presence of the sulphate of lime of sea-water becomes carbonate of lime and sulphate of ammonia.[3] The great majority of the accumulations formed of animal remains are calcareous. Those organisms which secrete their lime as calcite produce much more durable skeletons or tests than those which accumulate it in the form of aragonite. Hence among geological formations aragonite shells have in large measure disappeared.[4]

In fresh water, accumulations of animal remains are represented by the *marl* of lakes—a white, chalky deposit consisting of the mouldering remains of *Mollusca*, *Entomostraca*, and partly of fresh-water algæ. On the sea-bottom, in shallow water, they consist of beds of shells, as in oyster-banks. Under favourable conditions, extensive deposits of limestone are now being formed on the sea-floor in tropical latitudes. Mr. Murray, from observations made during the *Challenger* voyage, estimates that in a square mile of the tropical ocean down to a depth of 100 fathoms there are more than 16 tons of calcareous matter in the form of animal and vegetable organisms.[5] These surface organisms, when dead, are continually falling to the bottom, where their remains accumulate as a soft ooze. On the floor of the West Indian seas, where an extraordinarily abundant fauna is supported by the plentiful supply of food brought by the great ocean currents which enter that region from the South Atlantic, a calcareous deposit is being formed out of the hard parts of the animals that live on the bottom (mollusks, echinoderms, corals, alcyonoids, annelids, crustacea, &c.), mingled with what may fall from the upper water. This deposit accumulates as a vast submarine plateau or series of broad banks, and is comparable in extent to some of the more important limestones of older geological time. Some portions of it have here and there (Barbados, Guadeloupe, Cuba, &c.) been elevated above the sea, so that its composition and structure can be studied. The organisms in these upraised limestones are the same as those which still live, and form a similar limestone in the surrounding seas. In Yucatan the rock is perforated with caverns, one of which is 70 fathoms deep.[1]

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[1] Julien, *op. cit.* 396. Sollas, *Ann. Mag. Nat. Hist.* Nov. Dec. 1880. J. Roth, 'Allgem. Chem. Geologie,' p. 576, and Dr. von Ollech's pamphlet cited *ante*, p. 478.

[2] *Brit. Assoc.* 1881, sects. p. 584.

[3] *Proc. Roy. Soc. Edin.* xvii. (1889), p. 89.

[4] Sorby, Presidential Address Geol. Soc. 1879; P. F. Kendall, *Geol. Mag.* 1883, p. 497; V. Cornish and P. F. Kendall, *Geol. Mag.* 1888, p. 60. See *postea*, Book V. § ii. 2.

[5] *Proc. Roy. Soc. Edin.* x. (1880), p. 508.

Here and there considerable deposits of broken shells have been produced by the accumulation of the excrement of fishes, as Verrill has pointed out on the north-eastern coasts of the United States. Deposits of broken shells raised above sea-level either by breakers and winds or by subterranean movements, are solidified into more or less compact shelly limestone. Extensive beds of this nature, composed mainly of species of *Arca*, *Lutraria*, *Mactra*, &c., form islands fronting the shores of Florida, and likewise underlie the soil of that State. Some of the shells still retain their colours. The whole mass is in layers 1 to 18 inches thick, quite soft before exposure to the air, but hardening thereafter, and much of it exhibiting a confused crystallization.[2] It is known locally as Coquina. The calcareous dunes of Bermuda have been already referred to (p. 336).

Coral-reefs.[3]—But the most striking calcareous formations now in progress are the reefs and islands of coral. These vast masses of rock are formed by the continuous growth of various genera and species of corals, in tracts where the mean temperature is not lower than 68° Fahr. Coral-growth is prevented by colder water, and by the fresh and muddy water discharged into the sea by large rivers. One of the essential conditions for the formation of coral-reefs is abundance of food for the reef-builders, and this seems to be best supplied by the great equatorial currents. It is observed that on the eastern coasts of Africa, Central America, and Australia, bathed by ocean currents, extensive coral-reefs flourish, while on the western coasts, in corresponding latitudes, where no such powerful currents flow, only isolated patches of coral exist.[4]

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[1] A. Agassiz, *Amer. Acad.* xi. (1882), p. 111: and his "Three Cruises of the *Blake*."

[2] H. D. Rogers, *Brit. Assoc. Rep.* 1834, p. 11.

[3] See Darwin, 'The Structure and Distribution of Coral Islands,' 1842; 2nd edit. 1874; Dana, 'Corals and Coral Islands,' 1872; 2nd edit. 1890; Jukes's 'Narrative of Voyage of H.M.S. *Fly*,' 1847; C. Semper, *Zeitsch. Wissen. Zool.* xiii. (1863), p. 558; *Verhandl. Phys. Med. Gesellsch.* Wurzburg, Feb. 1868; 'Die Philippinen und ihre Bewohner,' 1869, p. 100; J. J. Rein, *Senckenb. Naturf. Ges.* Wurzburg, 1869-70, p. 157. Murray, *Proc. Roy. Soc. Edin.* x. p. 505, xvii. (1889), p. 79; A. Agassiz, *Mem. Amer. Acad.* xi. (1882), p. 107; *Bull. Mus. Compar. Zool. Harvard*, 1889, No. 3. C. P. Sluiter, on the coral-reefs of the Java Sea, *Natuurkund. Tijd. Nederlandsch. Indië.* xlix. (1890); J. Walther, on the coral-reefs of the Sinai peninsula, *Abhand. Math.-Phys. Kön. Sachs. Gesell.* xiv. (1888); H. B. Guppy, *Trans. Roy. Soc. Edin.* xxxii. (1885), 'The Solomon Islands,' 1887; J. C. Bourne, *Nature*, 1888, pp. 414, 546; J. C. Wharton, *ibid.* p. 393; A. Heilprin, "The Bermuda Islands," 1889, *Proc. Acad. Nat. Sci. Philadelphia*, 1890, p. 303; Jukes Brown and Harrison, Barbados, *Quart. Journ. Geol. Soc.* xlvii. (1891), p. 197; Walther, *Peterm. Mitth. Ergänz.* No. 102 (1891).

[4] A. Agassiz, *Amer. Acad.* xi. (1882), p. 120.

Darwin and Dana have shown that reef-building corals cannot live at depths of more than about fifteen or twenty fathoms; they appear, indeed, not to thrive below a depth of six or seven fathoms. They cannot survive exposure to sun and air, and consequently are unable to grow above the level of the lowest tides. They are likewise prevented from growing by the presence of much mud in the water. Various observations and estimates have been made of the rate of growth of coral. Individual specimens of *Mœandrina* have been found to increase from half an inch to an inch in a year, and others of *Madrepora* have grown three inches in the same time.[1] Specimens of *Orbicella*, *Manicina*, and *Isophyllia*, taken from the submarine telegraph-cable between Havana and Key West, showed a growth of from one to two and a half inches in about seven years. A. Agassiz estimates that in the Florida reef the corals could build up a reef from a depth of seven fathoms to the surface in 1000 or 1200 years.[2] When coral-reefs begin to grow, either fronting a coast-line or on a submarine bank, they continue to advance outward, the living portion being on the outside, while on the inside the mass consists of dying or dead coral, which becomes a solid white compact limestone. In the coral area of the Pacific there are, according to Dana, 290 coral-islands, besides extensive reefs round other islands. The Indian Ocean contains some groups of large coral-islands; others occur in the Red Sea. Reefs of coral occur less abundantly in the tropical parts of the Atlantic, among the West Indian Islands and on the Florida coast, but they are absent from the Pacific side of Central America—a fact attributed by Prof. Agassiz not to a cold marine current, as suggested by Prof. Dana, but to the enormous amount of mud poured into the sea on this side during the rainy season.[3] The great reef of Australia is 1250 miles long and from 10 to 90 miles broad.

Coral-rock, though formed by the continuous growth of the polyps, gradually loses any distinct organic structure, and acquires an internal crystalline character like an ancient limestone, owing to the infiltration of water through its mass, whereby calcium-carbonate is carried down and deposited in the pores and crevices, as in a growing stalactite. Great quantities of calcareous sand and mud are produced by the breakers which beat upon the outer edge of the reefs. This detritus is partly washed up upon the reefs, where, being cemented by solution and redeposit, it aids in their consolidation, sometimes acquiring an oolitic structure;[4] but much of it is swept away by the ocean currents and distributed over the sea-floor, the water becoming milky with it after a storm.[5] Around volcanic islands much lava-detritus may be mixed with the coral-sand and mud. Thus at Hawaii, where great abrasion by the waves takes place on the ends of the lava-streams which have run out to sea, large quantities of olivine sand are formed, the grains of this mineral varying from the size of a bean or pea downwards to the finest particles. This sand

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[1] Dana, 'Corals and Coral Islands,' 2nd edit. 1890, p. 123.

[2] *Amer. Acad.* xi. (1882), p. 129. See also *Bull. Mus. Comp. Zool. Harvard*, xx. (1890), p. 61.

[3] *Bull. Mus. Comp. Zool.* xxiii. (1892), p. 70.

[4] See Dana's 'Corals and Coral Islands,' pp. 152, 194; A. Agassiz, *Mem. Amer. Acad.* xi. (1882), p. 128.

[5] A. Agassiz mentions that after a storm, the sea is sometimes discoloured by this silt to a distance of six to ten miles from the outer reef, and he adds that he has seen between two and three inches of fine silt deposited in the interval between two tides after a prolonged

Fig 182 – View of an Atoll or Coral Island.

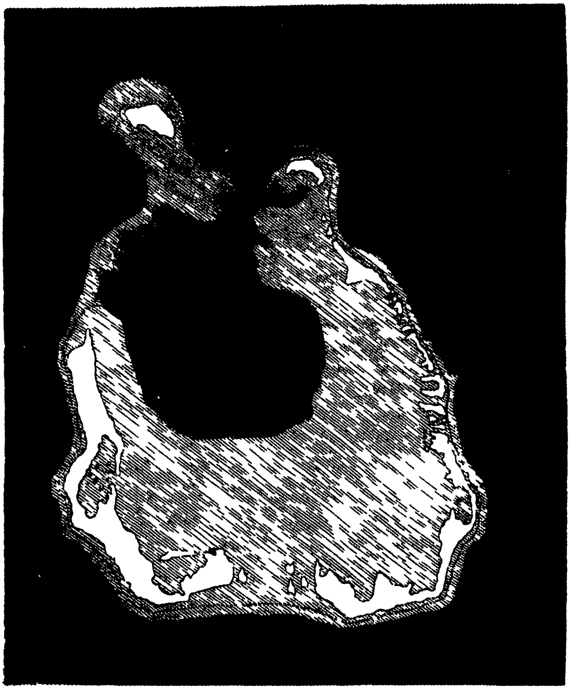

Fig. 183 —Chart of Keeling Atoll, Indian Ocean (after Darwin)
The white portion represents the reef above sea level, the inner shaded space the lagoon, of which the deepest portion is marked by the darker tint

storm *Amer. Acad.* xi p. 126. The total area of sea-floor covered with coral sand and mud is estimated by Messrs Murray and Irvine at 3,219,800 square miles. *Proc Roy. Soc. Edin.* xvii (1889), p 82 becomes mixed with the coral detritus, and is also interstratified with it in layers.[1]

As already mentioned (p. 290), the formation of coral islands has been explained by Darwin on the hypothesis of a subsidence of the sea-floor. The circular islands, or atolls, rising in mid-ocean, have the general aspect shown in Fig. 182. Their external form may be understood from the chart (Fig. 183), and their structure and the character of their surface from the section (Fig 184). They rise with sometimes tolerably steep slopes from a depth of 2000 feet and upwards, until they reach the surface of the sea. But as the coral polyps do not live at a greater depth than about 15 or 20 fathoms, and could not have grown upward therefore from the bottom of a deep sea, Darwin inferred that the sites of these coral reefs had undergone a progressive subsidence, the rate of their upward growth keeping pace, on the whole, with that of their depression On this view, what is termed a *Fringing Reef* (A B, Fig. 185) would first be formed fronting the land (L) between the limit of the 20-fathom line and the sea-level (s s). Growing upward until it reached the surface of the water, it would be exposed to the dash of the waves, which would break off pieces of the coral and heap them upon the reef. In this way islets would be formed upon it, which, by successive accumulations of materials thrown up by the breakers or brought by winds, would remain permanently above water. On these islets, palms and other plants, whose seeds might be drifted from distant or adjoining land, would take root and flourish. Inside the reef, there would be a shallow channel of water, communicating, through gaps in the reef, with

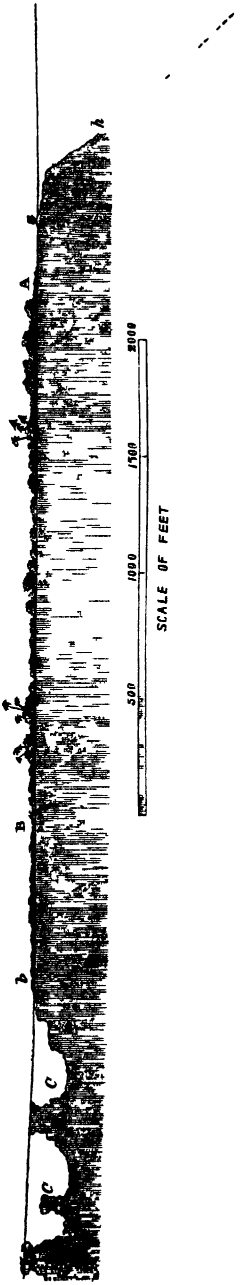

Fig 184 —Section of a Coral Reef
A B, Portion above tide mark (a b), covered with vegetation and habitable, C C, edge of lagoon, with insular masses of coral (D D) the open ocean lies to the right of the slope a h

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[1] W L Green, *Journ Roy. Geol Soc. Ireland*, iv. (1887), p. 140. This author suggestively points out the resemblance of such a mingling of calcareous material and magnesian silicate to the mingled limestones, serpentines and ophicalcites of the crystalline schists. Sollas, *Proc Royal Dublin Soc.* (1891), p. 124.

the main ocean outside. Fringing reefs of this character are of common occurrence at the present time. In the case of a continent, they front its coast for a long distance, but they may entirely surround an island.

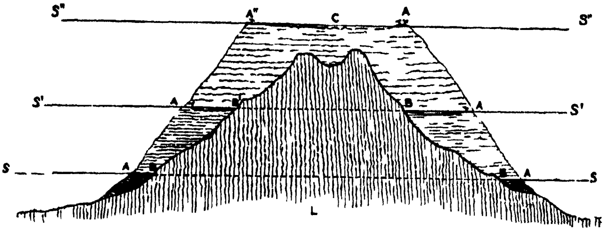

Fig. 185.—Diagram illustrating Darwin's theory of the formation of Atolls.

If, according to the Darwinian explanation, the site of a fringing reef undergoes depression at a rate sufficiently slow to allow the corals to keep pace with it, the reef may be conceived to grow upward as fast as the bottom sinks downward. As the reef grows mainly on its upper seaward edge, the lagoon channel inside will become deeper and wider, while, at the same time, the depth of water outside will increase until a *Barrier*

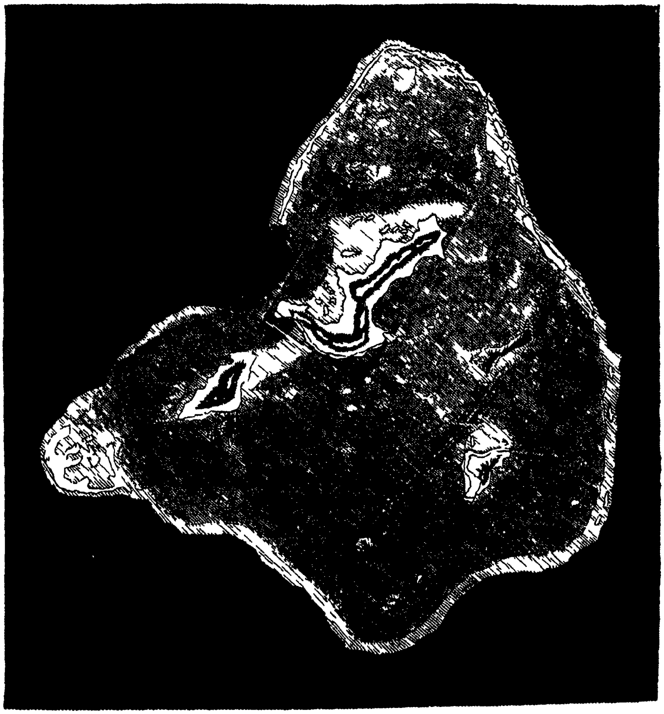

Fig. 186.—Chart of Gambier Islands, Pacific Ocean (after Beechy).

Reef (A′ B′, Fig. 185) is formed. In Fig. 186, for example, the Gambier Islands (1248 feet high) are shown to be entirely surrounded by an interrupted barrier reef, inside of which lies the lagoon. Prolonged slow depression would continually diminish the area of the land thus encircled, while the reef might retain much the same size and position. At last the final peak of the original island might disappear under the lagoon (C, Fig. 185), and an *Atoll*, or true coral-island, would be formed (A″ A″, Fig. 185, and Figs. 182 and 183). Should any more rapid or sudden downward movement take place, it might carry the atoll down beneath the surface, like the Great Chagos bank in the Indian Ocean, which is a submarine atoll.

This simple and luminous explanation of the history of coral-reefs accorded well with all the known facts, and led up to the impressive conclusion that a vast area of the Pacific Ocean, fully 6000 geographical miles from east to west, has undergone a recent subsidence, and may be slowly sinking still.

Mr. Darwin's views having been universally accepted by geologists, coral-islands have been regarded with special interest as furnishing proof of vast oceanic subsidence. In the year 1868, C. Semper pointed to some cases of atolls which, he said, could not be explained by Darwin's theory. The Pelew Islands, at the western end of the Caroline archipelago, show true atolls at their northern extremity, while at their southern end, only 60 miles away, there are raised coral-reefs, and an island entirely destitute of reefs. Semper considered that the atolls had grown up under the influence of peculiar conditions of marine currents and erosion, simultaneously with elevation rather than subsidence.[1] In 1870 J. J. Rein cited the case of Bermuda as one capable of explanation by upgrowth of calcareous accumulations from the bottom without subsidence.[2] More recently, Mr. Murray, whose researches in the *Challenger* Expedition led him to make detailed examination of many coral reefs, has suggested that barrier-reefs do not necessarily prove subsidence, seeing that they may grow outward from the land upon the top of a talus of their own débris broken down by the waves, and may thus appear to consist of solid coral which had grown upward from the bottom during depression, although only the upper layer, 20 fathoms or thereabouts in thickness, is composed of solid, unbroken coral growth. He points out that in the coral-seas the islands appear to have always started on volcanic ejections, at least that all the non-calcareous rock now visible is of volcanic origin. Where the submarine peak lay below the inferior limit of coral growth, it may have been brought up to the requisite level by the gradual accumulation of the remains of organisms.[3] Where the original eminence rose above the sea, the projecting portion (Fig. 187) may be supposed to have been cut down to the lower limit of breaker action (*a a*), so as to offer a platform on which corals might build reefs (*i k*) up to the level of high water (*b b*). Or with less denudation, or a loftier cone, a nucleus of the original volcano might remain as an island (Fig. 188), from the sides of which a barrier reef might grow outward, on a talus of its own débris (*r r*), and maintain a steep outer slope. According to this view the breadth of a reef ought, in some degree, to be a measure of its antiquity.

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[1] See Semper's papers quoted in footnote on p. 485. In the Appendix to the second edition of his 'Coral Reefs' (p. 223) Mr. Darwin replies to Semper's criticism, maintaining that his objections present no insuperable difficulty in the theory of subsidence.

[2] See paper cited in footnote on p. 485.

[3] "A submarine peak," says Professor A. Agassiz, "is built up by the carcases of the invertebrates that live upon it, and for which the pelagic fauna serves in part as food," *Bull. Mus. Comp. Zool. Harvard*, xvii. No. 3 (1889), p. 127.

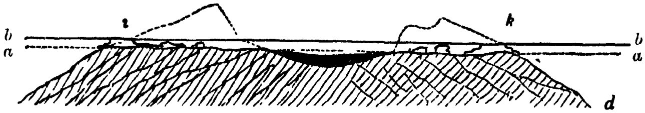

Fig. 187.—Section of a volcanic cone of loose ashes supposed to have been thrown up on the sea-floor and to have reached the sea-level (*B.*)

To the obvious objection that this explanation requires the existence of so many volcanic peaks just at the proper depth for coral-growth, and that the number of true atolls is so great, Mr. Murray replies that in several ways the limit for the commencement of coral-growth may be reached. Volcanic islands may be reduced by the waves to mere shoals (Fig. 187) like Graham's Island, in the Mediterranean. On the other hand, submarine volcanic peaks, if originally too low, may conceivably be brought up to the coral-zone by the constant deposit of the detritus of marine life (foraminifera, radiolaria, pteropods, &c.), which as above stated, is found to be very abundant in the upper waters, whence it descends as a kind of organic rain into the depths. Mr. Murray holds also that the dead coral, attacked by the solvent action of the sea-water, is removed in solution both from the lagoon (which may thus be deepened) and from the dead part of the outer face of the reef, which may in this way acquire greater steepness.[1]

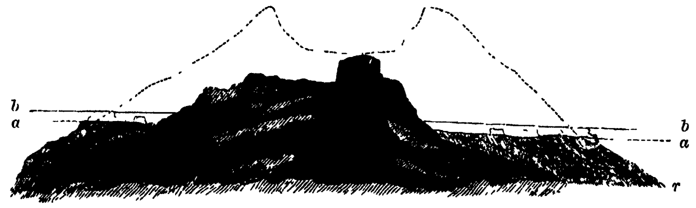

Fig. 188.—Section of denuded volcanic island with lava nucleus and surrounding coral-reef (*B.*)

Professor A. Agassiz has arrived at similar conclusions from detailed explorations among the coral-reefs and submarine banks of the West Indian seas and the Hawaiian Islands. He believes that barrier-reefs and atolls have arisen without the aid of subsidence, upon a platform prepared for them by the upward growth of submarine calcareous banks, under the most favourable condition of ocean-currents, temperature, and food.[1]

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[1] *Proc. Roy. Soc. Edin.* 1880, p. 505, *ante*, pp. 38, 441, 442.

That the wide-spread oceanic subsidence demanded by Darwin's theory cannot be demonstrated by coral-reefs must now, I think, be conceded. The co-existence of fringing and barrier-reefs, and of atolls, in the same neighbourhood with proofs of protracted stability of level or even with evidence of upheaval, likewise the successive stages whereby a true atoll may be formed without subsidence, have been demonstrated so clearly in the West Indian region, that we must admit the possibility that the same mode of formation may extend all over the coral-seas. At the same time, it must be granted that the necessary conditions for the formation of barrier-reefs and atolls might sometimes be brought about by subsidence. So long as a suitable bottom is provided for coral-growth it is probably immaterial whether this is done by the submergence of land or by the ascent of the sea-floor. That subsidence has in some cases taken place seems to be proved by the depth of some atoll-lagoons—40 fathoms—unless this depth can be supposed to be due to solution by sea-water, and not to the progressive deepening during a subsidence with which the upward growth of the reef could keep pace.

Ooze.—The bed of the Atlantic and other oceans is covered with a calcareous ooze formed of the remains of *Foraminifera*, chiefly species of the genus *Globigerina*. It has been observed that in these deep-sea deposits, the larger and relatively thinner pelagic shells are rare or absent at greater depths than 2000 fathoms, while the thicker-shelled varieties abound. This has been referred to the solvent action of sea-water, whereby the more fragile forms are attacked and removed in solution (*ante*, pp. 38, 441). Among abysmal deposits, foraminiferal ooze ranks next in abundance to the red and grey clays of the deep sea (p. 457). It is a pale-grey marl, sometimes red from peroxide of iron, or brown from peroxide of manganese; and it usually contains more or less clay, even with occasional fragments of pumice. It covers an area of the North Atlantic probably not less than 1300 miles from east to west, by several hundred miles from north to south. The total area of ocean-bottom occupied by globigerina-ooze is estimated at 47,752,500 square miles, the mean depth of the surface of the deposit below sea-level is computed to be 1996 fathoms, and the mean proportion of carbonate of lime in the ooze 64·53 per cent.[2]

The consolidation of a soft calcareous ooze or a mass of broken shells, corals, and other calcareous organisms, effected by the percolation of water containing carbonic acid (*ante*, pp. 365, 454, 486), is most rapid with copious evaporation, as, for instance, on coral-reefs where exposure to the air in the interval between two tides suffices for the deposit of a thin crust of hard limestone over a surface of broken coral or coral-sand.[3] Recently-upraised limestone and coral-rock have in some places assumed a crystalline structure by this process, and the more delicate organisms have disappeared from them. But the calcareous deposits may acquire, even under the sea, sufficient cohesion to be capable of being broken up into blocks. On the submarine plateau off Florida, the trawl or dredge frequently brings up large fragments of the limestone now in course of formation on the bottom, consisting of the dead carcases of the very species that live upon the surface of the growing deposit.[1]

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[1] *Amer. Acad.* xi. (1882), p. 107; *Bull. Mus. Comp. Zool. Harvard*, xvii. (1889), No. 3. See also the papers of Messrs. Guppy, Wharton, Bourne, and Sluiter, cited, *ante*, p. 485.

[2] Murray and Irvine, *Proc. Roy. Soc. Edin.* xvii. (1889), p. 82.

[3] A. Agassiz, *Amer. Acad.* xi. (1882), p. 128.

2. Siliceous deposits formed from animal exuviæ are illustrated by another of the deep-sea formations brought to light by the *Challenger* researches. In certain regions of the western and middle Pacific Ocean, the bottom was found to be covered with an ooze consisting almost entirely of *Radiolaria*. These minute organisms occur, indeed, more or less abundantly in almost all deep oceanic deposits. From the deepest sounding taken by the *Challenger* (4475 fathoms, or more than 5 miles) a radiolarian ooze was obtained (Fig. 189). The spicules of sponges likewise furnish materials towards these siliceous accumulations. The number of marine plants and animals which secrete silica is so great, and the proportion of that constituent in sea-water so minute that some difficulty has been felt to account satisfactorily for the vast quantities of

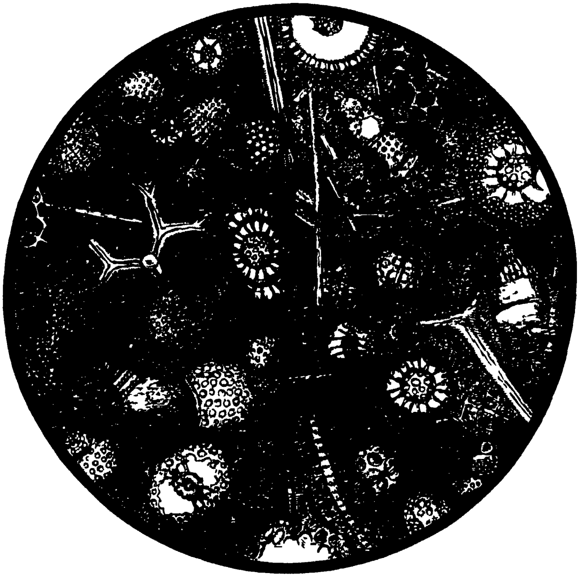

Fig. 189.—Radiolarian Ooze,

Dredged up by the *Challenger* Expedition, from a depth of 4475 fathoms, in Lat. 11° 24′ N., Long. 143' 10′ E. Magnified 100 diameters. This is from the deepest abyss whence organisms have yet been obtained.

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[1] A. Agassiz, *op. cit.* p. 112. An account of the upraised oceanic deposits of Barbados is given by Messrs. Jukes Brown and Harrison, *Quart. Journ. Geol. Soc.* xlviii. (1892), p. 170. Some of these deposits present a close resemblance to those ascertained by dredging to be seen in progress of accumulation in deep parts of the ocean.

silica continually being abstracted from the ocean by organic agencies. Messrs. Murray and Irvine, however, as already stated, have shown that an appreciable amount of fine clay is present even in the water of mid-ocean, and they have ascertained by actual experiments with living diatoms that these plants can obtain their silica from diffused clay in suspension.[1]

3. Phosphatic deposits,[2] in the great majority of cases, betoken some of the vertebrate animals, seeing that phosphate of lime enters largely into the composition of their bones and occurs in their excrement (p. 141). The most typical modern accumulations of this nature are the guano beds of rainless islands off the western coasts of South America and Southern Africa. In these regions, immense flocks of sea-fowl have, in the course of centuries, covered the ground with an accumulation of their droppings to a depth of sometimes 30 to 80 feet, or even more. This deposit, consisting chiefly of organic matter and ammoniacal salts, with about 20 per cent of phosphate of lime, has acquired a high value as a manure, and is being rapidly cleared off. It could only have been preserved in a rainless or almost rainless climate. In the west of Europe, isolated stacks and rocky islands in the sea are often seen to be white from the droppings of clouds of sea-birds; but it is merely a thin crust, which is not allowed to grow thicker in a climate where rains are frequent and heavy. From observations made on phosphatic deposits such as the phosphatic chalk of France, Belgium, and England, it is evident that phosphate of lime derived from the decomposition of animals (fish, &c.) may be held in solution and gather round any organic body, or fill its cavities and replace original carbonate of lime. Grains and concretions of phosphate are thus formed, especially in the interior of shells and foraminifera.[3]

Wherever terrestrial mammalia congregate, and especially where they die and leave their carcases, phosphatic deposits may be formed if the conditions are favourable for the preservation of the remains. Caves haunted by hyænas serve as receptacles not only for the bones and excrement of these animals but also for bones of the various animals which they have dragged there as food. Hence in limestone countries "osseous breccias" are often found below the layer of stalagmite on the floor. Again, along the swampy margins of lakes and salt-marshes the bodies of wild animals are often mired in the boggy ground and perish there, and their bodies gradually sink below the surface. Hence phosphatic accumulations arise sometimes on an extensive scale, as has happened in different parts of the United States.[4]

In connection with the organic deposits of the sea-floor, further reference may be made here to the chemical processes in progress there, and to the probable part taken in these processes by living organisms and decaying animal matter. The transformation of sulphate of lime into carbonate, which may now be regarded as the chief source of the calcareous constituents of marine plants and animals, takes place on a gigantic scale in the ocean. The precipitation of manganic oxide and its segregation in concretions, often round organic centres (p. 458), presents a close analogy to the formation of concretionary bog-iron ore through the operation of the humus acids in stagnant water. The crystallization of silicates observed during the *Challenger* expedition is possibly also to be connected with the action of organic compounds (p. 459). The formation of flint concretions has been for many years a vexed question in geology. The constant association of flints with traces, more or less marked, of former abundant siliceous organisms seems to make the inference irresistible, that the substance of the flint has been precipitated through the agency of these creatures. The silica has first been abstracted from sea-water by living organisms. It has then been re-dissolved and re-deposited (probably through the agency of decomposing organic matter), sometimes in amorphous concretions, sometimes replacing the calcareous parts of echini, mollusks, &c., while the surrounding matrix was, doubtless, still a soft watery ooze under the sea.[1]

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[1] Murray and Irvine on siliceous deposits of modern seas, *Proc. Roy. Soc. Edin.* xviii. (1891), p. 229, and *ante*, p. 450.

[2] A useful compendium of information on these deposits is given by R. A. F. Penrose in *Bull. U. S. Geol. Surv.* No. 46 (1888) already cited (p. 142).

[3] A. F. Renard and T. Cornet, *Bull. Acad. Roy. Belg.* xxi. (1891), p. 126. A. Strahan, *Quart. Journ. Geol. Soc.* xlvii. (1891), p. 356.

[4] Penrose, *Bull. U. S. Geol. Surv.* No. 46 (1888), p. 127.

§ 4. Man as a Geological Agent.

No survey of the geological workings of plant and animal life upon the surface of the globe can be complete which does not take account of the influence of man—an influence of enormous and increasing consequence in physical geography; for man has introduced, as it were, an element of antagonism to nature. Not content with gathering the fruits and capturing the animals which she has offered for his sustenance, he has, with advancing civilisation, engaged in a contest to subdue the earth and possess it. His warfare, indeed, has often been a blind one, successful for the moment, but leading to sure and sad disaster. He has, for instance, stripped off the woodland from many a region of hill and mountain, gaining his immediate object in the possession of their stores of timber, but thereby laying bare the slopes to parching droughts or fierce rains. Countries once rich in beauty, and plenteous in all that was needful for his support, are now burnt and barren, or washed bare of their soil. It is only in comparatively recent years that he has learnt the truth of the aphorism—"*Homo Naturæ minister et interpres.*"

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[1] See Wallich, *Q. J. Geol. Soc.* xxxvi. p. 68; Sollas, *Ann. and Mag. Nat. Hist.* 5th series, vi. p. 437; and *ante*, pp. 141, 483; *Brit. Assoc.* 1882, sects. p. 549; Hull and Hardman, *Trans. Roy. Dublin. Soc.* new series (1878), vol. i. p. 71. Julien observes that a substance corresponding to humus appears to enter universally into the constitution of the oceanic oozes, resulting from the decomposition of organisms and containing a high percentage of silica (*Proc. Amer. Assoc.* xxviii. p. 359). Consult also the paper of Messrs. Murray and Irvine already cited (*Proc. Roy. Soc. Edin.* xviii. (1891), p. 229) and the suggestive experiments there described as to the solution of silica in sea-water containing living and dead organisms.

But now, when that truth is coming more and more to be recognised and acted on, man's influence is none the less marked. His object still is to subdue the earth, and he attains it, not by setting nature and her laws at defiance, but by enlisting her in his service. Within the compass of this volume it is impossible to give more than merely a brief outline of so vast a subject.[1] The action of man is necessarily confined mainly to the land, though it has also to some extent influenced the marine fauna. It may be witnessed on climate, on the flow of water, on the character of the terrestrial surface, and on the distribution of life.

1. On Climate.—Human interference affects meteorological conditions—(1) by removing forests and laying bare to the sun and winds areas which were previously kept cool and damp under trees, or which, lying on the lee side, were protected from tempests; as already stated, it is supposed that the wholesale destruction of the woodlands formerly existing in countries bordering the Mediterranean has been in part the cause of the present desiccation of these districts, while in the Tyrol the great increase and destructiveness of the debacles has been attributed to the wholesale deforesting of that region, and the consequent exposure of the soil to rain and melted snow; (2) by drainage, the effect of this operation being to remove rapidly the discharged rainfall, to raise the temperature of the soil, to lessen the evaporation, and thereby to diminish the rainfall and somewhat increase the general temperature of a country; (3) by the other processes of agriculture, such as the transformation of moor and bog into cultivated land, and the clothing of bare hillsides with green crops or plantations of coniferous and hard-wood trees.

2. On the Flow of Water.—(1) By increasing or diminishing the rainfall man directly affects the circulation of water over the land. (2) By the drainage-operations, which cause the rain to run off more rapidly than before, he increases floods in rivers. (3) By wells, bores, mines, or other subterranean works, he interferes with underground waters and consequently with the discharge of springs. (4) By embanking rivers he confines them to narrow channels, sometimes increasing their scour, and enabling them to carry their sediment further seaward, sometimes causing them to deposit it over the plains and raise their level.

3. On the Surface of the Land.—Man's operations alter the aspect of a country in many ways:—(1) by changing forest into bare mountain, or clothing bare mountain with forest; (2) by promoting the growth or causing the removal of peat-mosses; (3) by heedlessly uncovering sand-dunes, and thereby setting in motion a process of destruction which may

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[1] See Marsh's 'Man and Nature,' a work which, as its title denotes, specially treats of this subject, and of which a new and enlarged edition was published in 1874 under the title of 'The Earth as modified by Human Action.' It contains a copious bibliography. See also Rolleston, *Jour. Roy. Geog. Soc.* xlix. p. 320, and works cited by him, particularly De Candolle, 'Géographie botanique raisonnée,' 1855; Unger's 'Botanische Streifzuge,' in *Sitzber. Vienna Acad.* 1857–1859; J. G. St. Hilaire, 'Histoire naturelle générale des Règnes Organiques,' tom. iii. 1862; Oscar Peschel, 'Physische Erdkunde;' Link, 'Urwelt und Alterthum' (1822); G. A. Koch, *Jahrb. Geol. Reichsanst.* xxv. (1875), p. 114.

convert hundreds of acres of fertile land into waste sand, or by prudently planting the dunes with sand-loving herbage or pines, and thus arresting their landward progress; (4) by so guiding the course of rivers as to make them aid him in reclaiming waste land and bringing it under cultivation; (5) by piers and bulwarks, whereby the ravages of the sea are stayed, or by the thoughtless removal from the beach of stones which the waves had themselves thrown up, and which would have served for a time to protect the land; (6) by forming new deposits either designedly or incidentally. The roads, bridges, canals, railways, tunnels, villages, and towns with which man has covered the surface of the land will in many cases form a permanent record of his presence. Under his hand, the whole surface of civilised countries is very slowly covered by a stratum, either formed wholly by him, or due in great measure to his operations, and containing many relics of his presence. The soil of old cities has been increased to a depth of many feet by the rubbish of his buildings: the level of the streets of modern Rome stands high above that of the pavement of the Cæsars, and this again above the roadways of the early Republic. Over cultivated fields potsherds are turned up in abundance by the plough. The loam has risen within the walls of our graveyards, as generation after generation has mouldered there into dust.

4. On the Distribution of Life.—It is under this head, perhaps, that the most subtle of human influences come. Some of man's doings in this dominion are indeed plain enough, such as the extirpation of wild animals, the diminution or destruction of some forms of vegetation, the introduction of plants and animals useful to himself, and especially the enormous predominance given by him to the cereals and to the spread of sheep and cattle. But no such extensive disturbance of the normal conditions of the distribution of life can take place without carrying with it many secondary effects, and setting in motion a wide cycle of change and of reaction in the animal and vegetable kingdoms. For example, the incessant warfare waged by man against birds and beasts of prey, in districts given up to the chase, leads sometimes to unforeseen results. The weak game is allowed to live, which would otherwise be killed off and give more room for the healthy remainder. Other animals, which feed perhaps on the same materials as the game, are from the same cause permitted to live unchecked, and thereby to act as a further hindrance to the spread of the protected species. But the indirect results of man's interference with the régime of plants and animals still require much prolonged observation.[1]

This outline may suffice to indicate how important is the place filled by man as a geological agent, and how in future ages the traces of his interference may introduce an element of difficulty or uncertainty into the study of geological phenomena.

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[1] See on the subject of man's influence on organic nature, the paper by Professor Rolleston, quoted on the previous page, and the numerous authorities cited by him.

BOOK IV.

GEOTECTONIC (STRUCTURAL) GEOLOGY,

OR THE ARCHITECTURE OF THE EARTH'S CRUST.

THE nature of minerals and rocks and the operations of the different agencies by which they are produced and modified having been discussed in the two foregoing books, there remains for consideration the manner in which these materials have been arranged so as to build up the crust of the earth. Since by far the largest visible portion of this crust consists of sedimentary or aqueous rocks, it will be of advantage to treat of them first, noting both their original characters, as resulting from the circumstances under which they were formed, and the modifications subsequently effected upon them. Many superinduced structures, not peculiar to sedimentary, but occurring more or less markedly in all rocks, may be conveniently described together. The distinctive characters of the igneous or eruptive rocks, as portions of the architecture of the crust, will then be described; and lastly, those of the crystalline schists and other associated rocks to which the name of metamorphic is usually applied.

PART I. STRATIFICATION AND ITS ACCOMPANIMENTS.

The term "stratified," so often applied as a general designation to the aqueous or sedimentary rocks, expresses their leading structural feature. Their materials, laid down for the most part on the bed of the sea and the floors of lakes and rivers, under conditions which have been already discussed in Book III., are disposed in layers or strata, an arrangement characteristic of them alike in hand-specimens and in cliffs and mountains (Figs. 190, 191, 252 and 253). Not that every morsel of aqueous rock exhibits evidence of stratification. But it is this feature which in a sufficiently large mass of material is least frequently absent. The general characters of stratification will be best understood from an explanation of the terms by which they are expressed.

Forms of Bedding.—Laminæ are the thinnest paper-like layers in the planes of deposit of a stratified rock. Such fine layers only occur where the material is fine-grained, as in mud or shale, or where fine scales of some mineral have been plentifully deposited, as in micaceous sandstone. In some laminated rocks, the laminæ cohere so firmly that they can hardly be split open, and the rock will break more readily across them than in their direction. More usually, however, the planes of lamination serve as convenient divisional surfaces by means of which the rock can be split open.[1] The cause of this structure has been generally assigned to intermittent deposit, each lamina being assumed to have partially consolidated before its successor was laid down upon it. Mr. Sorby, however, has recently suggested that in fine argillaceous rocks it may be a kind of cleavage-structure (see pp. 314, 545), due to the pressure of the overlying rocks, with the consequent squeezing out of interstitial water and the rearrangement of the argillaceous particles in lines perpendicular to the pressure.[2]

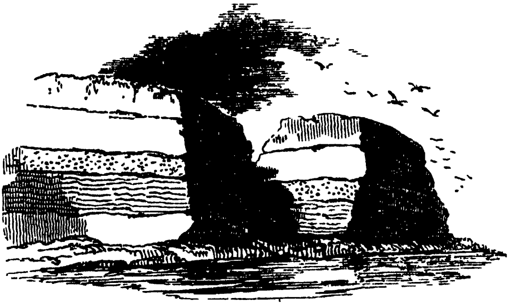

Fig. 190.—Sea-cliff showing a series of Stratified Rocks (*B.*)

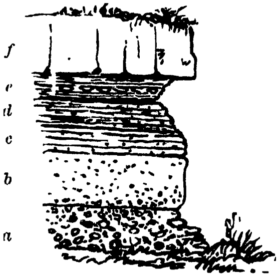

Fig. 191.—Section of Stratified Rocks. *a*, conglomerate ; *b*, thick-bedded pebbly sandstone ; *c*, thin-bedded sandstone ; *d*, shelly sandstone ; *e*, shale with ironstone nodules ; *f*, limestone with marine organisms.

Much may be learnt as to former geographical and geological changes by attending to the characters of strata. In Fig. 191, for example, there is evidence of a gradual diminution of movement in the waters in which the layers of sediment were deposited. The conglomerate (*a*) points to currents of some force ; the sandstones (*b c d*) mark a progressive quiescence and the advent of finer sediment ; the shales (*e*) show a deposition of fine mud and accretion of ferrous carbonate into nodules round organic remains ; while the shell-limestone (*f*) proves that the water no longer carried much sediment, but had become clear enough for an abundant growth of marine organisms. The existence, therefore, of alternations of fine laminæ of deposit may be conceived as pointing to tranquil conditions of slow intermittent sedimentation, where silt has been borne at intervals and has fallen over the same area of undisturbed water. Regularity of thickness and persistence of lithological characters among the laminæ may be taken to indicate periodic currents, of approximately equal force, from the same quarter. In some cases, successive tides in a sheltered estuary may have been the agents of deposition. In others, the sediment was doubtless brought by recurring river-floods. A great thickness of laminated rock, like the massive shales of Palæozoic formations, suggests a prolonged period of quiescence, and probably, in most cases, slow, tranquil subsidence of the sea-floor. On the other hand, the alternation of thin bands of laminated rock with others coarser in texture and non-laminated, indicates considerable oscillation of currents from different quarters bearing various qualities and amounts of sediment.[1]

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[1] M. Daubrée has proposed the term *diastrome* to express the splitting of rocks along their bedding planes. *Bull. Soc. Géol. France* (3), x. p. 137.

[2] *Quart. Journ. Geol. Soc.* xxxvi. p. 67 (1880).

Strata or Beds are layers of rock varying from an inch or less up to many feet in thickness. A stratum may be made up of numerous laminæ, if the nature of the sediment and mode of deposit have favoured the production of this structure, as has commonly been the case with the finer kinds of sediment. In materials of coarser grain, the strata, as a rule, are not laminated, but form the thinnest parallel divisions. Strata, like laminæ, sometimes cohere firmly, but are commonly separable with more or less ease from each other. In the former case, we may suppose that the lower bed before its consolidation was followed by the deposit of the upper. The common merging of a stratum into that which overlies it must no doubt be regarded as evidence of more or less gradual change in the conditions of deposit. Where the overlying bed is abruptly separable from that below it, the interval was probably of some duration, though occasionally the want of cohesion may arise from the nature of the sediment, as for instance, where an intervening layer of mica-flakes has been laid down. A stratum may be one of a series of similar beds in the same mass of rock, as where a thick sandstone includes many individual strata, varying considerably in their respective thicknesses; or it may be complete and distinct in itself, as where a band of limestone or ironstone runs through the heart of a series of shales. As a general rule, the conclusion appears to be legitimate that stratification, when exceedingly well-marked, indicates slow intermittent deposition, and that when weak or absent it points to more rapid deposition, intervals and changes in the nature of the sediment and in the direction of force of the transporting currents being necessary for the production of a distinctly stratified structure.

Lines due to original stratification must be carefully distinguished from other divisional planes which, though somewhat like them, are of entirely different origin. Five kinds of fissility may be recognised among rocks:—1st, *lamination* of original deposit; 2nd, *cleavage*, as in slate; 3rd, *shearing*, as near faults and thrust-planes (pp. 316, 544); 4th, *foliation*, as in schists; 5th, *flow-structure*, when extremely developed in some lavas, wherein, by the development of steam-holes or spherulitic concretions and the drawing-out of these into planes during the movement of the molten mass, a kind of fissility is produced which at first might be mistaken for the lamination of deposit. Close-set joints likewise give rise to divisional planes, which, like cleavage, may now and then deceive an observer by their resemblance to stratification.

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[1] For a series of experiments to illustrate the origin of the sedimentation of the coal-measures, see H. Fayol, *Bull. Soc. Industrie Minérale, St. Etienne*,' 2me sér. xv. (1886). 'Etudes sur le terrain houiller de Commentry,' with atlas.

Originally the planes of stratification, in the great majority of cases, were nearly horizontal. As most sedimentary rocks are of marine origin, and have accumulated on the shallower slopes of the sea-floor, they have generally had from the first a slight inclination seawards; but, save on rapidly shelving shores, the angle of declivity has been usually so slight as to be hardly appreciable by the eye. Slight departures from this predominant horizontality would be caused where sediment accumulated unequally, or where the floor on which deposition took place was of an undulating or more markedly uneven character.

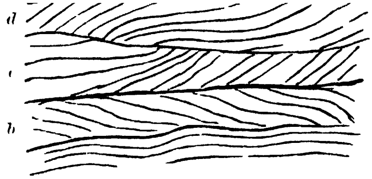

Fig. 192.—Section of False-bedded Strata.

False-bedding, Current-bedding.—Some strata, particularly sandstones, are marked by an irregular lamination, wherein the laminæ, though for short distances parallel to each other, are oblique to the general stratification of the mass, at constantly varying angles and in different directions (*a b c d* in Fig. 192). This structure, known as false-bedding or current-bedding, points to frequent changes in the direction of the currents by which the sediment was carried along and deposited. Sand pushed over the bottom of a sheet of water by varying currents tends to accumulate irregularly in banks and ridges, which often advance with a steep slope in front. The upper and lower surfaces of the bank or bed of sand (* * in Fig. 192) may remain parallel with each other as well as with the underlying bottom (*a*), yet the successive laminæ composing it may lie at an angle of 30° or even more. We may illustrate this structure by the familiar formation of a railway embankment. The top of the embankment, on which the permanent way is to be laid, is kept level; but the advancing end of the earthwork shows a steep slope over which the workmen are constantly discharging waggon-loads of rubbish. Hence the embankment, if cut open longitudinally, would present a "false-bedded" structure, for it would be found to consist of many irregular layers inclined at a high angle in the direction in which the formation of the mound had advanced. Among geological formations of all ages, occasional sections of the upper surfaces of such false-bedded strata show the singular irregularity of the structure, and bring vividly before the imagination the feeble shifting currents by which the sediment was drifted about in the shallow water where it accumulated (Fig. 193). A noticeable feature is the markedly lenticular character of false-bedded strata. Even where the usual diagonal lamination is feeble or absent this lenticular structure may remain distinct

(Fig. 194). Examples may also be observed, in which, while all the beds are well laminated, in some the laminæ run parallel with the general bedding, and in others obliquely (Fig. 195). Though current-bedding is most frequent among sandstones, or markedly arenaceous strata, it may be observed occasionally in detrital formations of organic origin, as in a section (Fig. 196) by De la Beche, where a portion of one of the calcareous members of the Jurassic series of England, consists of beds composed mostly of organic fragments with a strongly marked current-bedding (*a a*), while others, formed of muddy layers and not obliquely laminated (*b b*), point to intervals when, with the cessation of the silt-bearing currents, the water became still enough to allow the mud suspended in it to settle on the bottom.[1]

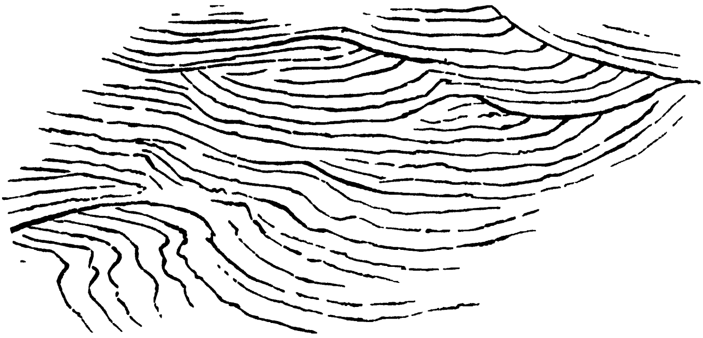

Fig. 193.—Plan of upper surface of a False-bedded Coal-measure Sandstone, Nolton Haven, Pembrokeshire. (By the late Professor John Phillips.)

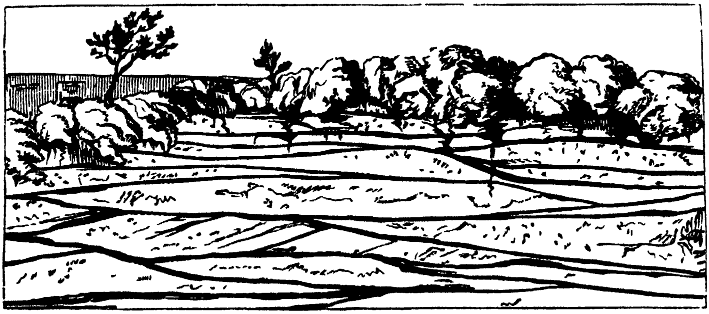

Fig. 194.—False-bedded Strata, Old Red Sandstone, Ross, Herefordshire. (By the late Sir Henry James, R.E.)

Intercalated Contortion.—Diagonal lamination is sometimes contorted as well as steeply inclined, and highly contorted beds are interposed between others which are undisturbed and horizontal. Curved and contorted lamination is of frequent occurrence among Palæozoic sandstones. In Fig. 196, an example is given from one of the oldest formations in Britain, and in Fig. 197 another from one of the youngest.

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[1] 'Geological Observer,' p. 536. The memoir by H. Fayol cited on p. 500, is accompanied with an atlas which contains many excellent illustrations of the exceedingly irregular stratification of the Coal-measures.

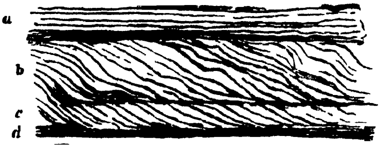

Fig 195 —Ordinary lamination and current lamination, Upper Old Red Sandstone, Clowes Bay, Waterford

a, d, e, beds of sand and silt deposited horizontally and apparently from mechanical suspension, b, c, beds of sand which have been pushed along the bottom

The cause of this structure is not well understood. Among glacial deposits local examples of contortion occur, which may be accounted for by the intercalation and subsequent melting of sheets of frozen mud,

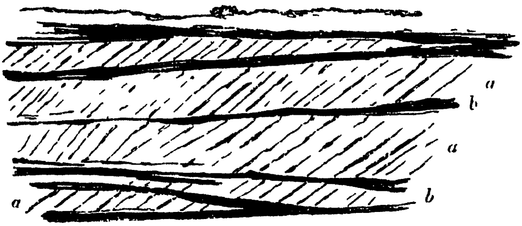

Fig 196 —Section in the Forest Marble, the Butts, Frome, Somerset

a, a, beds formed of broken shells, fish-teeth, pieces of wood, and oolitic grains; b, b, layers of clay

or by the stranding of heavy masses of drift-ice upon still unconsolidated sand and mud. The removal of mineral matter in solution (as among saliferous and gypseous deposits) leads to the subsidence and crumpling

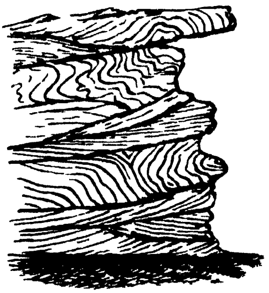

Fig. 197 —Contorted false-bedding, Torridon Sandstone, Gairloch.

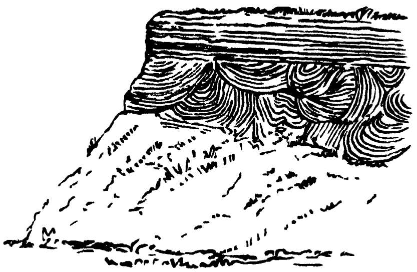

Fig 198 —Contorted Post Tertiary sands and clays, near Forres

of overlying beds. The hydration of anhydrite (pp. 298, 345), by augmenting the volume of the mass, subjects the adjacent strata to crushing and contortion. It is possible that some of the extraordinary labyrinthine and complex contortions of certain schistose rocks may be due to the subsequent crumpling of strata already full of diagonal or contorted lamination.

Irregularities of Bedding due to Inequalities of Deposition or of Erosion.—A sharp ridge of sand or gravel may be laid down under water by current-action of some strength. Should the motion of the water diminish, finer sediment may be brought to the place and be deposited around and above the ridge. In such a case, the stratification of the later accumulation may end off abruptly against the flanks of the older ridge, which will appear to rise up through the overlying bed. Appearances of this kind are not uncommon in coal-fields, where they are known to the miners as "rolls," "swells," or "horses' backs." A structure exactly the reverse of the preceding, where a stratum has been scooped out before the deposition of the layers which cover it, has also often been observed in mining for coal, when it is termed a "want."

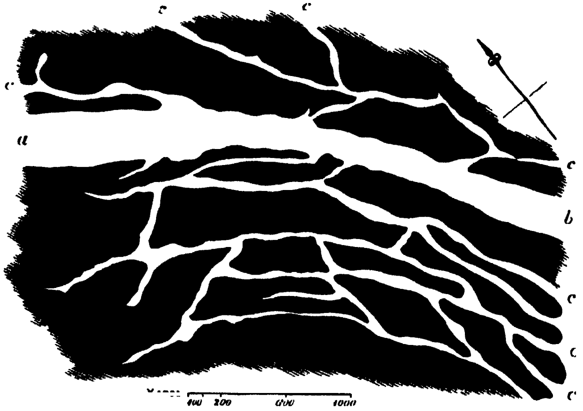

Fig. 199.—Plan of channels in coal, Forest of Dean (after Buddle).

Channels have been cut out of a coal-seam, or rather out of the bed of vegetation which ultimately became coal, and these winding and branching channels have been filled up with sandy or muddy sediment. The accompanying plan (Fig. 199) represents a portion of a remarkable series of such channels traversing the Coleford High Delf coal-seam in the Forest of Dean. The chief one, locally known as the "Horse" (*a b*), has been traced for about two miles, and varies in width from 170 to 340 yards. It is joined by smaller tributaries (*c c*), which run for some way approximately parallel to it. The coal has either been prevented from accumulating in contemporaneous water-channels, or, while still in the condition of soft bog-like vegetation, has been eroded by streamlets flowing through it.[1] A section drawn across such a buried channel exhibits the structure represented in Fig. 200, where a bed of fire-clay (*e*), full of roots and evidently an old soil, supports a bed of coal (*d*) and of shale (*c*), which, during the deposition of this series of strata, have been cut out into a channel at *f*. A deposition of sand (*b*) has then filled up the excavation, and a layer of mud (*a*) has covered up the whole.

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[1] Buddle, *Geol. Trans.* vi. (1842), p. 215

Currents of very unequal force and transporting power may alternate in such a way that after fine silt has for some time been accumulated, coarse shingle may next be swept along, and may be so irregularly bedded with the softer strata as to simulate the behaviour of an intrusive rock (Fig. 201).[1] The section (Fig. 202) taken by De la Beche from a cliff of Coal-measures on the coast of Pembrokeshire, shows a deposit of shale (*a*) that during the course of its formation was eroded by a channel at *b*, into which sand was carried; after which, the deposit of fine mud recommenced, and similar shale was again laid down upon the top of the sandy layer, until, by a more potent current, the shale deposit was cut away on the left side of the section, and a series of sandbeds (*c*) was laid down upon its eroded edges. An interruption of this kind, however, may not seriously disturb the earlier conditions of a deposit, which, as shown in the same section, may be again resumed, and new layers (*d*) may be laid down conformably over the whole. Among the lessons to be learnt

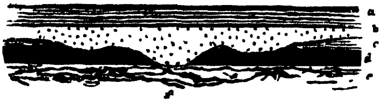

Fig. 200.—Section of a channel in a coal-seam (*B.*)

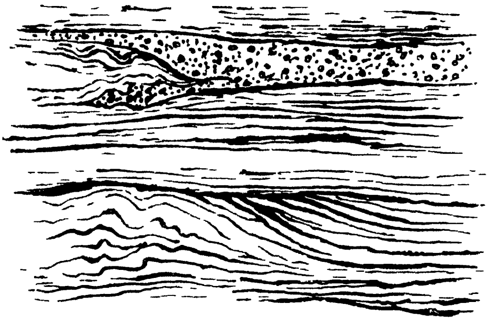

Fig. 201.—Irregular bedding of coarse and fine Lower Silurian detritus. Flanks of Glydyr, N.E. of Snowdon (*B.*)

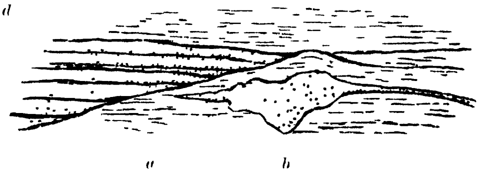

Fig. 202.—Contemporaneous Erosion and Deposit (*B.*)

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[1] De la Beche, 'Geol. Observer,' p. 533.

from such sections of local irregularity, one of the most useful is the reminder that the inclination of strata may not always be due to subterranean movement. In Fig. 203, for example, the lower strata of shale and sandstone are nearly horizontal. The upper thick sandstone (*b′*) has been cut away towards the left, and a series of shales (*a′*) and a coal-seam (*c′*) have been deposited against and over it. If the sandstone was then level, the shales must have been laid down at a considerable angle, or, if these were deposited in horizontal sheets, the earlier sandstone must have accumulated on a marked slope. As deposition continued, the inclined plane of sedimentation would gradually become horizontal until the strata were once more parallel with the series *a b c* below. A structure of this kind, not unfrequent in the Coal-measures, must be looked upon as a larger kind of false-bedding, where, however, terrestrial movement may sometimes have intervened.

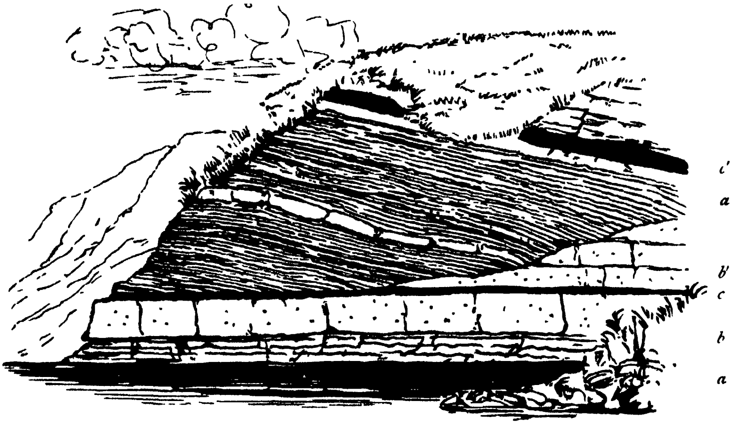

Fig. 203.—Contemporaneous Erosion with inclined and horizontal deposits, in Coal-measures, Kello Water, Sanquhar, Dumfriesshire.

a, *a′*, shales and ironstones ; *b*, *b′*, sandstones ; *c*, *c′*, coal-seams.

In the instances here cited, it is evident that the erosion took place, in a general sense, during the same period with the accumulation of the strata. For, after the interruption was covered up, sedimentation went on as before, and there is usually an obvious close sequence between the continuous strata. Though it may be impossible to decide as to the relative length of the interval that elapsed between the formation of a given stratum and that of the next stratum which lies upon its eroded surface, or to ascertain how much depth of rock has been removed in the erosion, yet, when the structure occurs among conformable strata, evidently united as one lithologically continuous series of deposits, we may reasonably infer that the missing portions are of small moment, and that the erosion was merely due to the irregular and more violent action of the very currents by which the sediment of the successive strata was supplied.

The case is very different when the eroded strata, besides being inclined at a different angle from those above them, are strongly marked off by lithological distinctions, particularly when fragments of them occur in the overlying deposits. In some of the coal-mines in central Scotland, for instance, deep channels have been met with entirely filled with sand, gravel, or clay belonging to the general superficial drift of the country. These channels have evidently been water-courses worn out of the Coal-measure strata at a comparatively recent geological period, and subsequently buried under glacial accumulations. There is a complete discordance between them and the Palæozoic strata below, pointing to the existence of a vast interval of time.

Surface-markings.—The surface of many beds of sandstone is marked with lines of wavy ridge and hollow, such as may be seen on a sandy shore from which the tide has retired, on the floors of shallow lakes and of river-pools, and on surfaces of dry wind-blown sand. To these markings the general name of Ripple-mark has been given. They have been produced by an oscillation of the medium (water or air) in which the loose sand has lain. In water, an oscillatory movement, sometimes also with a more or less marked current, is generated by wind blowing on its surface. The sand-grains are carried backwards and forwards. By degrees, inequalities of surface are produced, which give rise to vortices in the water. In irregular ripple-mark, the direct current carries the sand up the weather-slope, while the vortex pushes it up the lee-slope, until the surface of the sand becomes mottled over with little prominences or dunes. In regular ripple-mark, the forms are produced by water oscillating relatively to the bottom and the consequent establishment of a series of vortices.[1] The long gentle slope towards the wind, and the short steep slope away from it, are well marked (Fig. 204, compare also Fig. 91). Considerable diversity in the form of the ripple, however, may be observed (as at *a b c* in Fig. 205), depending on conditions of wind, water, and sediment which have not been thoroughly studied. No satisfactory inference can be drawn from the existence of ripple-marks as to the precise

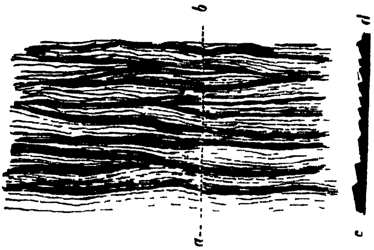

Fig. 204.—Plan and section of Rippled Surface.

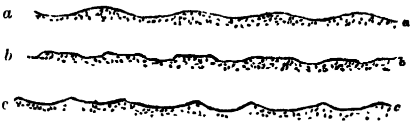

Fig. 205.—Sections of Ripple-marks.

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[1] Prof. Darwin, *Proc. Roy. Soc.* xxxvi. (1883), p. 18. See also H. C. Sorby, *Edin. New Phil. Journ.* new ser. iii. iv. v. vii. ; *Geologist*, ii. (1859), p. 137 ; A. R. Hunt. *Proc. Roy. Soc.* xxxiv. p. 1 ; C. de Candolle, *Arch. Sci. Phys. Nat. Geneva*, ix. (1883) ; M Forel, in same volume.

depth of water in which the sediment was accumulated. As a rule, it is in water of only a few feet or yards in depth that this characteristic surface is formed. But it may be produced at any depth to which the agitation caused by wind on the upper waters may extend (p. 438). Examples of it may be observed among arenaceous deposits of all ages from pre-Cambrian upwards. In like manner, we may frequently detect, among these formations, small isolated or connected linear ridges (rill-marks) directed from some common quarter, like the current-marks frequently to be found behind projecting fragments of shell, stones, or bits of seaweed on a beach from which the tide has just retired.

On an ordinary beach, each tide usually effaces the ripple-marks made by its predecessor, and leaves a new series to be obliterated by the next tide. In the process of obliteration, the tops of the ridges are levelled off (see *b* in Fig. 205), while sometimes the hollows, where they serve as receptacles for surface drainage, are deepened. Where the markings are formed in water which is always receiving fresh accumulations of sediment, a rippled surface may be gently overspread by the descent of a layer of sediment upon it, and may thus be preserved. By a renewal of the oscillation of the water another series of ripples may then be made in the overlying layers, which in turn may be buried and preserved under a renewed deposit of sand. In this way, a considerable thickness of such ripple-marked strata may be accumulated, as has frequently taken place among geological formations of all ages.

Sun-cracks, Rain-prints, Vestiges of former Shores.— One of the most fascinating parts of the work of a field-geologist consists in tracing the shores of former seas and lakes, and in endeavouring thereby to reconstruct the geography of successive geological periods. There are not a few pieces of evidence, which, though in themselves individually of apparently small moment, combine to supply him with reliable data. Among these he lays special emphasis upon the proofs that, during their deposition, strata have at intervals been laid bare to sun and air.

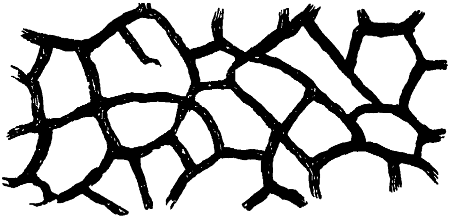

Fig. 206. Sun-cracked surface of mud or muddy sand.

The nature and validity of the arguments founded on this evidence will be best realised by the student if he can make observations at the margin of the sea, or of any inland sheet of water, which from time to time leaves tracts of mud or fine sand exposed to sun and rain. The way in which the muddy bottom of a dried-up pool cracks into polygonal cakes when exposed to the sun may be illustrated abundantly among sedimentary rocks. These desiccation-cracks, or sun-cracks (Fig. 206), could not have been produced so long as the sediment lay under water. Their existence therefore among any strata proves that the surface of rock on which they lie was exposed to the air and dried, before the next layer of water-borne sediment was deposited upon it.

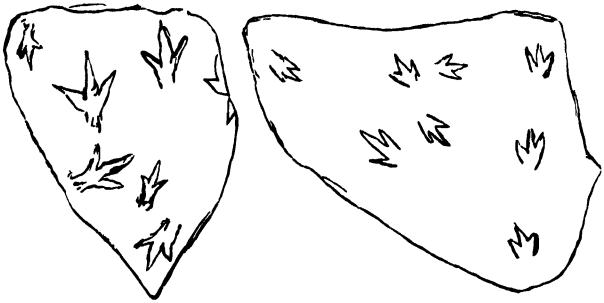

Fig. 207.—Footprints from the Triassic Sandstone of Connecticut (Hitchcock).

With these markings are occasionally associated prints of rain-drops. The familiar effects of a heavy shower upon a surface of moist sand or mud may be witnessed among rocks even as old as the Cambrian period. In some cases, the rain-prints are found to be ridged up on one side, in such a manner as to indicate that the rain-drops as they fell were driven aslant by the wind. The prominent side of the markings, therefore, indicates the side towards which the wind blew.

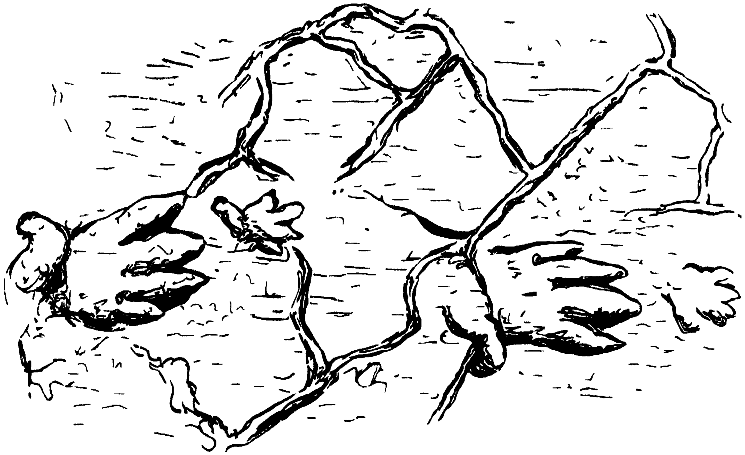

Fig. 208.—Footprints and Sun-cracks, Hildburghausen, Saxony (Sickler).

Numerous proofs of shallow shore-water, and likewise of exposure to the air, are supplied by markings left by animals. Castings, tubular burrows and trails of worms, tracks of mollusks and crustaceans, fin-marks of fishes, footprints of reptiles (Fig. 207), birds, and mammals, may all be preserved and give their evidence regarding the physical conditions under which sedimentary formations were accumulated. It may frequently be noticed that such impressions are associated with ripple-marks, rain-prints, or sun-cracks (Fig. 208); so that more than one kind of evidence may be gleaned from a locality to show that it was sometimes laid bare of water.

The more striking indications of littoral conditions being comparatively infrequent, the geologist must usually content himself with tracing the gravelly detritus, which suggests, if it does not always prove, proximity to some former line of shore. Such a section, for instance, as that depicted in Fig. 209 may often be found, where lower strata (*a*) having been tilted, raised into land, and worn away, have yielded materials for a coarse littoral boulder bed (*b*), over which, as it was carried down into deeper and clearer water, limestone eventually accumulated. Beds of conglomerate, especially where, as in this example, they accompany an unconformability in the stratification, are of much service in tracing the limits of ancient seas and lakes (see Part X.)

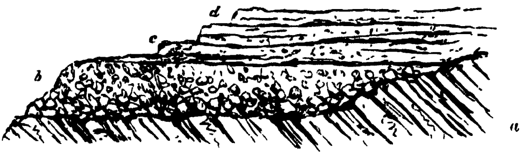

Fig. 209.—Section of a beach of early Mesozoic age, near Clifton, Bristol (*B.*)
a, Carboniferous limestone; *b*, dolomitic conglomerate—a mass of boulders and angular fragments of *a* (some of them almost two tons in weight), passing up into finer conglomerate *c*, with sandstone and marl, and thence into dolomitic limestone *d*.

Gas-spurts.—The surfaces of some strata, usually of a dark colour and containing organic matter, may be observed to be raised into little heaps of various indefinite shapes, not like the heaps associated with worm-burrows, connected with pipes descending into the rock, nor composed of different material from the surrounding sandstone or shale. These may be conjectured to be due to the intermittent escape of gas from decomposing organic matter in the original sand or mud, as we may sometimes witness in operation among the mud-flats of rivers and estuaries, where much organic matter is decomposing among the sediment. On a small scale, these protrusions of the upper surface of a deposit may be compared with the mud-lumps at the mouths of the Mississippi, already described (p. 399).

Concretions.—Many sedimentary rocks, more particularly clays, ironstones, and limestones, exhibit a concretionary structure. This arrangement may be part of the original sedimentation, or may be due to subsequent segregation from decomposition round a centre. Concretionary structures of contemporaneous origin, particularly in calcareous materials, may lie so closely adjacent as to form continuous or nearly continuous beds (Fig. 210). The Magnesian Limestone of Durham is built up of variously shaped concretionary masses, sometimes like cannon-balls, grape-shot, or bunches of coral. Connected with concretionary beds are the seams of gypsum, which may occasionally be observed to send out veins into other gypsum beds above and below them. De la Beche describes a section at Watchet, Somersetshire, where, amid the Triassic marls (*b b* in Fig. 211), beds of gypsum (*a a*) connect themselves by means of fibrous veins with the overlying and underlying beds.

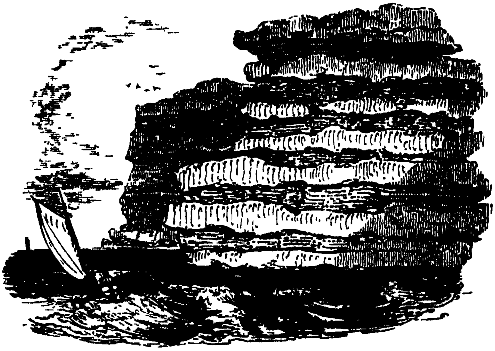

Fig. 210.—Section of alternations of shale and concretionary limestone (*B.*)

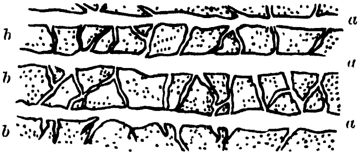

Fig 211.—Sections of beds and connecting strings of gypsum in the Trias, Watchet, Somersetshire (*B.*).

The most frequent form of concretions is that of isolated spherical, elliptical, or variously shaped nodules, disposed in certain layers of a stratum or dispersed irregularly through it (Fig. 212). They most commonly consist of ferrous or calcic carbonates, or of silica. Many clay-ironstone beds assume a nodular form, and this mineral occurs abundantly in the shape of separate nodules in shales and clay-rocks. The nodules have frequently formed round some organic body, such as a fragment of plant, a shell, bone, or coprolite. That the carbonate was slowly precipitated during the formation of the bed of shale in which its nodules lie, may often be satisfactorily proved by the lines of deposit passing continuously through the nodules (Fig. 213). In many cases, the internal first-formed parts of a nodule have contracted more than the outer and more compact crust; and have cracked into open polygonal spaces, which are commonly filled with calcite (Fig. 26). Such *septarian nodules*, whether

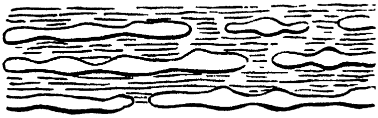

Fig. 212.—Concretions of limestone in shale.

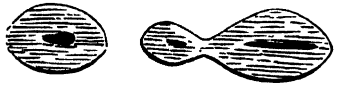

Fig. 213.—Concretions surrounding organic centres and exhibiting the continuation of the lines of stratification of the surrounding shales.

composed of clay-ironstone or limestone, are abundant in many shales, as in the Carboniferous and Liassic series of England.

Alluvial clays sometimes contain fantastically shaped concretions due to the consolidation of the clay by a calcareous or ferruginous cement round a centre. These are known in Scotland as fairy-stones, in the valley of the Rhine as Losspuppen, Lossmanchen, and in Finland as Imatra-stones (Fig. 214 and p. 332). They not uncommonly show the bedding of the clay in which they may have been formed. Their quaint imitative forms have naturally given rise to a popular belief that they are petrifications of various kinds of organic bodies and even of articles of human manufacture. In Norway they occur in glacial and post-glacial deposits up to heights of 360 feet above sea-level, and enclose remains of fishes (of which 16 species have been noticed), as well as other organisms.[1]

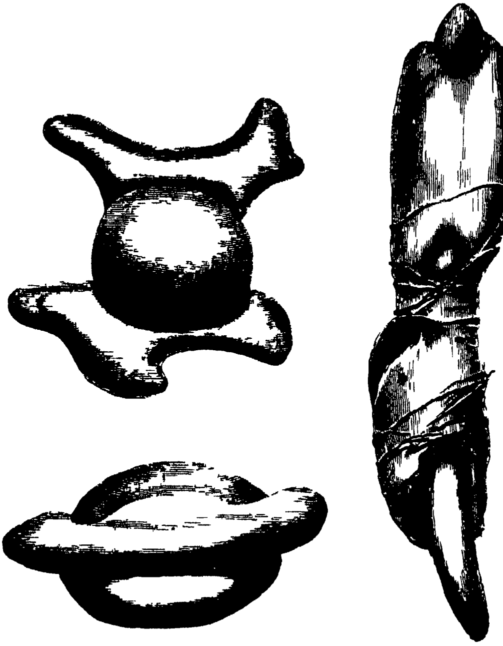

Fig 214 Clay concretions of alluvium (nat size)

Concretions of silica occur in limestone of many geological ages (p. 495). The flints of the English Chalk are a familiar example, but similar siliceous concretions occur in Carboniferous and Cambrian limestones. The silica, in these cases, has not infrequently been deposited round organic bodies, such as sponges, sea-urchins, and mollusks, which are completely enveloped in it, and have even themselves been silicified. Iron-disulphide often assumes the form of concretions, more particularly among clay-rocks, and these, though presenting many eccentricities of shape—round, like pistol-shot or cannon-balls, kidney-shaped, botryoidal, &c.—agree in usually possessing an internal fibrous radiated structure. Phosphate of lime is found as concretions in formations where the coprolites and bones of reptiles and other animals have been collected together (see p. 494).

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[1] Kjerulf, 'Geologie des sudl und mittl Norwegens' (1880), p. 5; R Collet, *Nyl Mag Nat* xxiii No. 3, p 11

Concretions produced subsequently to the formation of the rock occur in some sandstones, which, when exposed to the weather, decompose into large round balls. In other instances, a ferruginous cement is gradually aggregated by percolating water in lines which curve round so as to enclose portions of the rock. These lines, owing to abstraction of iron from within the spheroid and partly from without, harden into dark crusts, inside of which the sandstone becomes quite bleached and soft.[1] Some shales exhibit a concretionary structure in a still more striking manner, inasmuch as the concretions consist of the general mass of the laminated shale, and the lines of stratification pass through them and mark them out distinctly as superinduced upon the rock. Examples of this structure are not infrequent among the argillaceous strata of the Carboniferous system. The concretionary olive-green shales and mudstones of the Ludlow group, in the Upper Silurian system, exhibit on weathered surfaces, all the way from South Wales into central Scotland, a peculiar structure which consists in the development of concentric spheroids varying from less than an inch up to several feet in diameter, the successive shells being separated from each other by a fine dark ferruginous film (Fig. 215). The lines of stratification are sometimes well marked by layers of fossils, but the rock splits up mainly along the curved surfaces separating the concentric shells. Concretionary structures are found also in rocks formed from chemical precipitation, as for instance in beds of rock-salt. The pseudo-concretions probably due to pressure (stylolites) have been already described (p. 316).

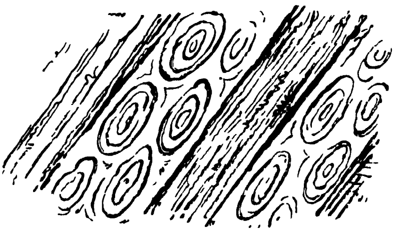

Fig. 215. Concretionary structure in Upper Silurian shales, Cwm-ddu, Llangammarch, Brecknockshire (*B.*)

Alternations and Associations of Strata.—Though great variations occur in the nature of the strata composing a mass of sedimentary rocks, it may often be observed that certain repetitions occur. Sandstones, for example, are found to be interleaved with shale above, and then to pass into shale; the latter may in turn become sandy at the top and be finally covered by sandstone, or may assume a calcareous character and pass up into limestone. Such alternations bring before us the conditions under which the sedimentation took place. A sandstone group indicates water of comparatively little depth, moved by changing currents, bringing the sand, now from one side, now from another. The passage of such a group into one of shale points to a diminution in the motion and transporting power of the water, perhaps to a sinking of the tract, so that only fine mud was intermittently brought into it. The advent of limestone above the shale serves to show that the water cleared, owing to a deflection of the sediment-carrying currents, or to continued and perhaps more rapid subsidence, and that foraminifera, corals, crinoids, mollusks, or other lime-secreting organisms, established themselves upon the spot. Shale overlying the limestone would tell of fresh inroads of mud, which destroyed the animal life that had been flourishing on the bottom; while a return of sandstone beds would mark how, in the course of time, the original conditions of troubled currents and shifting sandbanks returned. Such alternating groups of sandy, calcareous, and argillaceous strata are well illustrated among the Jurassic formations of England (Fig. 216).

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[1] See Penning, *Geol. Mag.* Dec. 2, iii. May 1876.

Certain kinds of strata commonly occur together, because the conditions under which they were formed were apt to arise in succession. One of the most familiar examples is the association of coal and fire-clay. In Britain a seam of coal is generally found to lie on a bed of fire-clay, or on some argillaceous stratum. The reason of this union becomes at once apparent when we learn that the fire-clay was the soil on which the plants grew that went to form the coal. Where the clay was laid down under suitable circumstances, vegetation sprang up upon it. This appears to have taken place in wide shallow lagoon-like expansions of the sea, bordering land clothed with dense vegetation, and to have been accompanied by slow, intermittent, but prolonged subsidence of the sea-bottom. Hence, during pauses of the downward movement, when the water shoaled, an abundant growth of water-loving or marshy plants sprang up on the muddy bottom, somewhat like the mangrove-swamps of the present day, and continued to flourish until the muddy soil was exhausted,[1] or until subsidence recommenced and the matted jungles, carried under the water, were buried under fresh inroads of sand or mud.

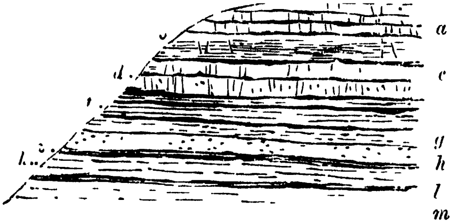

Fig. 216.—Section of strata from the base of the Lias down to the top of the Trias, Shepton Mallet (B.)
a, Grey Lias limestone and marls, b, earthy whitish limestone and marls; c, earthy white limestone; d, arenaceous limestone; f, grey marls; g, red marls; h, sandstone with calcareous cement; i, blue marl; k, red marl; l, blue marl; m, red marls.

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[1] Sterry Hunt has called attention to the fact that the underclays of the Coal-measures have generally been deprived of their alkalies by the vegetable growth which they supported. In the little coal-basins of France evidence has been obtained that much of the coal was formed out of vegetation that had been swept down and buried by rapid currents. See the Memoir of M. Fayol cited on. p. 500.

Each coal-field thus contains a succession of buried forests with a constant repetition of the same kind of intervening strata (Fig. 217).

For obvious reasons, conglomerate and sandstone occur together, rather than conglomerate and shale. The agitation of the water which could form and deposit coarse detritus, like that composing conglomerate, was too great to admit of the accumulation of fine silt. On the other hand, we may look for shale or clay rather than sandstone, as an accompaniment of limestone, inasmuch as when the gentle currents by which fine argillaceous silt was carried in suspension ceased, they would be succeeded by intervals of quiet clearing of the water, during which calcareous material might be elaborated either chemically or by the action of living organisms.

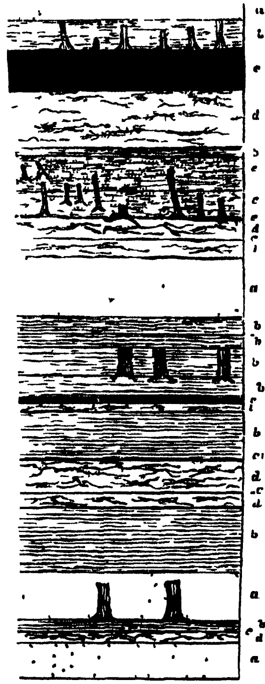

Fig. 217.—Succession of buried coal growths and erect tree stumps, Sydney Coal Field, Cape Breton, (R. Brown)[1]

a, sandstones, b, shales, c, coal seams, d, beds containing roots and stumps *in situ*

Relative persistence of Strata.—A little reflection will convince the student that all sedimentary rocks must thin out and disappear, and that even the most persistent, when regarded on the great scale, are local and lenticular accumulations. Derived from the degradation of land, they have accumulated near land. They are necessarily thickest in mass, as well as coarsest in texture, nearest to the source of supply, and become more attenuated and fine-grained as they recede from it. We have only to observe what takes place at the present time on lake-bottoms, estuaries, or sea-margins, to be assured that this is now, and must always have been, the law of sedimentation.

But while all sedimentary deposits must be regarded as essentially local, some kinds possess a far greater persistence than others. As a general rule, it may be said that the coarser the grain, the more local the extent of a rock. Conglomerates are thus by much the most variable and inconstant of all sedimentary formations. They suddenly sink down from a thickness of several hundred feet to a few yards or die out altogether, to reappear, perhaps further on, in the same wedge-like fashion Sandstones are less liable to such extremes of inconstancy, but they too are apt to thin away and to swell out again. Shales are much more persistent, the same zone being often traceable for many miles. Limestones sometimes occur in thick local masses, as among the Silurian formations, but they often also display remarkable continuity. Three thin limestone bands, each of them only two or three feet in thickness, and separated by a considerable thickness of intervening sandstones and shales, can be traced through the coal-fields of central Scotland over an area of at least 1000 square miles. Coal-seams also possess great persistence. The same seams, varying slightly in thickness and quality, may often be traced throughout the whole of an extensive coal-field.

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[1] See R Brown, *Quart Journ. Geol Soc.* vi. p. 115 ; and De la Beche, 'Geol. Observer,' p. 505.

What is thus true of individual strata may be affirmed also of groups of such strata. A thick mass of sandstone will be found as a rule to be more continuous than one of conglomerate, but less so than one of shale. A series of limestone beds usually stretches further than either arenaceous or argillaceous sediments. But even to the most extensive stratum or group of strata there must be a limit. It must end off, and give place to others, either suddenly, as a bank of shingle is succeeded by the sheet of sand heaped against its base, or, as is more usual, very gradually, by insensibly passing into other strata on all sides.

Great variations in the character of stratified rocks may frequently be observed in passing from one part of a country to another along the outcrop of the same rocks. Thus, at one end, we may meet with a thick series of sandstones which, traced in a certain direction, may be found passing into shales (Fig. 218). A group of strata may consist of massive conglomerates at one locality, and may graduate into fine fissile flagstones in another. A thick mass of clay may be found to alternate more and more with shelly sands as it is traced outward, until it loses its argillaceous nature altogether.

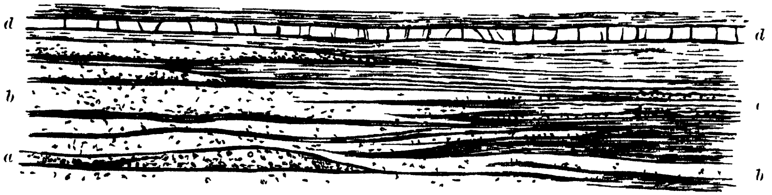

Fig. 218.—Section to illustrate the great lithological differences of contemporaneous deposits occupying the same horizon.
a, conglomerate; *b*, sandstone; *c*, shale; *d d*, limestone.

Interesting illustrations of such arrangements occur in the south-west of England, where what are now groups of hills, like the Mendip, Malvern, and other eminences formerly existed as islands in the Mesozoic sea. De la Beche pointed out that the upturned Carboniferous limestone (*a a* in Fig. 219) has formed the shore against which the coarse shingle of the dolomitic conglomerate (*b b*) accumulated; that the latter, traced away from its shore-line, passes on the same plane into red marl (*c*), and that during a gradual subsidence, the clays and limestones of the Lias (*d*) crept over the depressed shore-line. He likewise called attention to the important fact that, in such

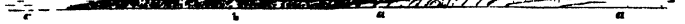

Fig. 219.—Section near Bristol to show how conglomerate may pass into clay along the same horizon.
B, Blaize Castle Hill; *s*, Mount Skitham (*B.*)

cases, a continuous zone of conglomerate may belong to many successive horizons. In Fig. 220 a section is given from one of the islands in the south-west of England, round which the Trias and Lias were deposited. Denudation has stripped off a portion of the overlying red marls. If the rest of the section to the left of the dotted line (*d d*) were removed, there would remain a continuous mass of conglomerate, which, in default of other evidence to the contrary, would be regarded as one bed laid down upon the sloping surface of limestone, instead of, what it really is, a series of shore gravels piled upon each other, and belonging to a consecutive series of deposits.

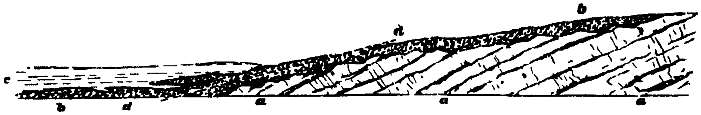

Fig. 220.—Section of part of the flank of the Mendip Hills (*B.*), showing the Carboniferous Limestone (*a a*) overlaid by dolomitic conglomerate (*b b*), and that by red marls (*c*).

Mere difference of lithological character, even within a limited geographical space, does not necessarily mean diversity of age. At the present day, coarse shingle may be formed along the beach, at the same time that the finest mud is being laid down on the same sea-bottom further from land. The existing differences of character between the deposits of the shore and of the opener sea would no doubt continue to be maintained, with slight geographical displacements, even if the whole area were undergoing subsidence, so that a thick group of littoral deposits might gather in one tract, and of deeper-water accumulations in another.

Among the formations of former geological periods, the same conditions of deposition appear sometimes to have continued for enormous periods. The thick Carboniferous Limestone of western Europe evidently accumulated during a slow subsidence, when the same conditions of clear water with abundant growth of crinoids, corals, &c., continued for a period vast enough to admit of the gradual growth of thousands of feet of calcareous matter. Traced northwards into Scotland, this massive limestone is gradually replaced by sandstones, shales, ironstones, and coal-seams. These strata prove that the deeper and clearer water of Belgium, central England, and Ireland passed northwards into muddy flats and sandy shoals, which at one time were overspread with coal-growths, and at another, owing to more rapid subsidence, were depressed beneath the clearer sea which brought with it the corals, crinoids, mollusks, &c., whose remains are now to be seen in intercalations of crinoidal limestone.

Influence of the Attenuation of Strata upon apparent Dip.—Where a thick mass of sedimentary materials rapidly thins away in a given direction, a deceptive resemblance to the effects of underground movement may be observed. If, for example, we suppose that on a perfectly level bottom, a series of sedimentary beds is accumulated at one place to a depth of 5000 feet, and that this series dies out in a distance of 80 miles, the inclination due to this attenuation will amount to a slope of about 62 feet in a mile. That this structure has not been without considerable influence on the apparent dip of stratified rocks has been well shown by Mr. W. Topley with reference to the Mesozoic rocks of the south-east of England.[1]

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[1] *Quart. Journ. Geol. Soc.* xxx. (1874), p. 186.

Overlap.—Sediment laid down in a subsiding region, wherein the area of deposit is gradually increased, spreads over a progressively augmenting surface. Under such circumstances, the later portions of a formation, or series of sedimentary accumulations, will extend beyond the limits of the older parts, and will repose directly upon the shelving bottom. This relation, called Overlap (Fig. 221), in which the higher or newer members are said to "overlap" the older, may often be detected among formations of all geological ages. It brings before us the shore-lines of ancient land-surfaces, and shows how, as these sank under water, the gravels, sands, and silts gradually advanced and covered them.

This structure must be carefully distinguished from Unconformability (*postea*, p. 641). In Overlap there is no break in the sequence of formations; the strata that overlap follow on continuously upon these which are overlapped. But in unconformability there is a break in the succession, the overlying rocks have been laid down on the previously uptilted and denuded edges of those below them. In Fig. 221, for example, the upper or Mesozoic formations (*d* to *i*) form an unbroken series, so do the lower or Palæozoic strata (*a b c*), but the latter have been disturbed and worn down before the deposition of the strata above them. The two series are said therefore to be unconformable.

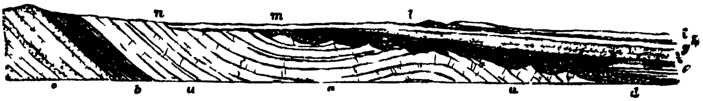

Fig. 221.—Section of Overlap in the Lower Jurassic series of the South-west of England (B.)

The Old Red Sandstone (*c*), Lower Limestone Shale (*b*), and Carboniferous Limestone (*a*) having been previously upraised and denuded, the older beaches (*d m*), laid down unconformably upon them, were successively covered by conformable Jurassic beds. The Lias (*e*), with its upper sands (*f*), is overlapped by the extension of the Inferior Oolite (*g*) completely across their edges, until this formation comes to rest directly on the Palæozoic strata at *n*. The corresponding extension of the overlying Fuller's Earth (*h l*) and limestone (*i*) has been removed by denudation.[1]

Relative Lapse of Time represented by Strata and by the Intervals between them.—Of the absolute length of time represented by any strata or groups of strata, no satisfactory estimates have yet been possible. Certain general conclusions may indeed be drawn, and comparisons may be made between different series of rocks. Sandstones full of false-bedding were probably accumulated more rapidly than finely-laminated shales or clays. It is not uncommon in certain Carboniferous sandstones to find huge sigillarioid and coniferous trunks imbedded in upright or inclined positions. Where, as in Fig. 222, the trees actually grew on the spot where their stems remain, it is evident that the rate of deposit of the sediment which entombed them must have been sufficiently rapid to have allowed a mass of twenty or thirty feet to accumulate before the decay of the wood. Of the durability of these ancient trees we of course know nothing; though modern instances are on record where, under certain circumstances, submerged trees may last for some centuries. We may conjecture that where upright or inclined stems are enveloped in one continuous stratum, the rate of accumulation was probably, on the whole, somewhat rapid. The general character of the strata among which such erect tree-trunks occur, obviously indicates extremely shallow water conditions with continuous or intermittent subsidence. Unless soon submerged, dead trees would be subject to speedy subaerial decomposition. It occasionally happens that an erect trunk has kept its position even during the accumulation of a series of strata around it (Fig. 223). We can hardly believe that in such cases any considerable number of years could have elapsed between the death of the tree and its final entombment. From the decayed condition of the interior of some imbedded trees, we may likewise infer that accumulation of sediment is not always an extremely slow process. Instances occur where, as Fig. 224, while sand and mud have been accumulating round the submerged stem, its interior has been rotting, so that eventually a mere hollow cylinder has been left, into which sediment and different plants (sometimes with the bodies of land animals) were introduced from above.[2] Large coniferous trunks (as in the neighbourhood of Edinburgh) have been imbedded in sandstone, and have had their

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[1] De la Beche, 'Geol. Observer,' p. 485.

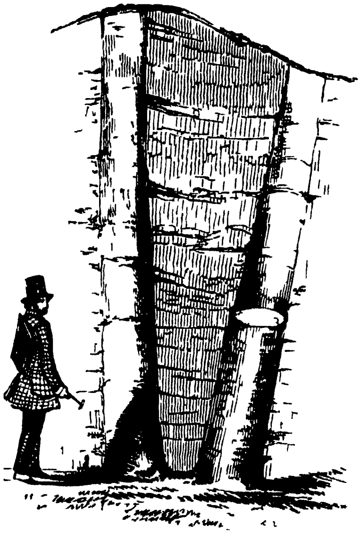

Fig. 222. Erect trunks of Sigillaria in sandstone, Cwm Llech, head of Swansea Valley, Glamorganshire. (Drawn by the late Sir W. E. Logan.)

These stems (the largest 5½ feet in circumference) formed part of a series in the same rock, their roots being imbedded in a seam of shale (an old soil) full of fern leaves, &c. The specimens were removed to the Museum of the Royal Institution of South Wales at Swansea.[1]

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[1] De la Beche, 'Geol. Observer,' p. 501.

[2] The hollow tree-trunks of the Nova Scotian coal-fields have yielded a most interesting series of terrestrial organisms—land snails and reptiles. For illustrations of trees in Coal-measure strata and the deposition of sediment round them see the Atlas to M. Fayol's Memoir cited on p. 500.

internal microscopic structure well preserved. In such examples, the drifted trees seem to have sunk with their heavier or root-end touching the bottom, and their upper end pointing upward in the direction of the current, like the snags of the Mississippi, and to have been completely buried in sediment before decay.

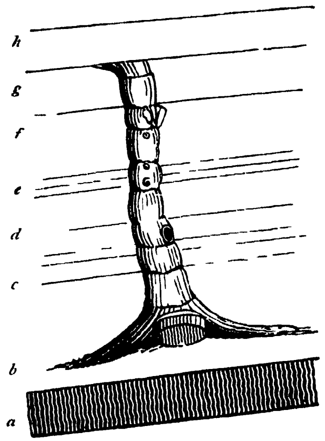

Fig. 223.—Erect tree trunk rising through a succession of strata, Killingworth Colliery, Newcastle (*B.*)

a, High Main Coal seam; *b*, bituminous shale; *c*, blue shale; *d*, compact sandstone; *e*, shales and sandstones; *f*, white sandstones; *g*, micaceous sandstone; *h*, shale.

Continuous layers of the same kind of deposit suggest a persistence of geological conditions; numerous alternations of different kinds of sedimentary matter point to vicissitudes or alternations of conditions. As a rule, we should infer that the time represented by a given thickness of similar strata was less than that shown by the same thickness of dissimilar strata, because the changes needed to bring new varieties of sediment into the area of deposit would usually require the lapse of some time for their completion. But this conclusion might often be erroneous. It would be best supported when, from the very nature of the rocks, wide variations in the character of the water-bottom could be established. Thus a group of shales followed by a fossiliferous limestone, would mark a period of slow deposit and quiescence, almost always of longer duration than would be indicated by an equal depth of sandy strata, pointing to more active sedimentation. Thick limestones, made up of remains of organisms which lived and died upon the spot, and whose remains are crowded together generation above generation, must have demanded prolonged periods for their formation.

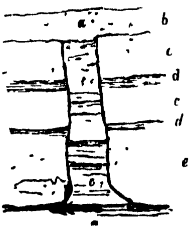

Fig. 224.—Erect tree trunk (*a a*) imbedded in sandstones (*c c*) and shales (*d d*), its interior filled with different sandy and clayey strata (*e e*), and the whole covered by a sandstone bed (*b*) (*B.*)

But in all speculations of this kind, we must bear in mind that the relative length of time represented by a given depth of strata is not to be estimated merely from thickness or lithological characters. It has already been pointed out that the interval between the deposit of two successive laminæ of shale may have been as long as, or even longer than, that required for the formation of one of the laminæ. In like manner, the interval needed for the transition from one stratum or kind of strata to another may often have been more than equal to the time required for the formation of the strata of either kind. But the relative chronological importance of the bars or lines in the geological record can seldom be satisfactorily discussed merely on lithological grounds. This must mainly be decided on the evidence of organic remains, as will be shown in Book V. By this kind of evidence, it can be made nearly certain that the intervals represented by strata were in many cases much shorter than those not so represented,—in other words, that the time during which no deposit of sediment went on at any particular locality was longer than that wherein deposit did take place.

Ternary Succession of Strata.—In following the order of sedimentation among the stratified rocks of the earth's crust, the observer will be led to remark a more or less distinct threefold arrangement or succession in which the sandy, muddy, and calcareous sediments have followed each other. Professor John Phillips and Mr. Hull have called attention to this structure, illustrating it by reference to the geological formations of Great Britain, while Professor Newberry, Dr. Sterry Hunt, and Principal Dawson have discussed it in relation to the stratigraphical series of North America. According to Mr. Hull a natural cycle of sedimentation consists of three phases ; 1st, a lower stage of sandstones, shales, and other sedimentary deposits, representing prevalence of land with downward movement; 2nd, a middle stage, chiefly of limestone, representing prevalence of sea with general quiescence and elaboration of calcareous organic formations; 3rd, an upper stage, once more of mechanical sediments indicative of proximity to land.[1] Where the strata are interrupted by disturbance and unconformability, we may suppose the cycle of sedimentation to have been completed by upheaval after prolonged subsidence. But where the continuity of the formations is unbroken, as it is over such vast tracts in North America, upheaval is not required, and the facts seem explicable, as Phillips long ago showed, on the idea of prolonged but intermittent subsidence. Let us suppose a downward movement to commence, and to depress successive sheets of gravel, shingle, sand, and other shallow water accumulations, derived from the erosion of neighbouring land. If the depression be comparatively rapid, the bottom may soon be carried beyond the reach of at least the coarser kinds of sediment, and marine lime-secreting organisms may afterwards begin to form a calcareous floor beneath the sea. Let us imagine further, that the subsidence ceases for a time, and that by the accumulation of organic remains, and partly also by the deposit of fine muddy sediment, the water is shallowed. With this gradual change of depth, the coarser detritus begins once more to be able to stretch seawards, and to overspread the limestones, which, under the altered circumstances, cease to be formed. A gradual silting up of the area takes place, marked by beds of sand and mud, until a renewal of the subsidence, either suddenly or slowly, restores the previous depth and clearness of water, and allows either the old marine organisms, which had been driven off, or their modified descendants to reoccupy the area and build new limestone.

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[1] Phillips, *Mem. Geol. Surv.* ii. ; 'Geol. Yorkshire,' ii. ; 'Geol. Oxford,' p. 293 ; Hull, *Quart. Jour. Sci.* July, 1869 ; Newberry, *Proc. Amer. Assoc.* 1873, p. 185 ; *Proc. Lyceum Nat. Hist. New York*, 2nd ser. No. 4, p. 122 ; Hunt, in Logan's 'Geology of Canada,' 1863, p. 627 ; *Amer. Journ. Sci.* (2nd series), xxxv. p. 167 ; Dawson, *Q. J. Geol. Soc.* xxii. p. 102 ; 'Acadian Geology,' p. 135. Compare on this subject E. van den Broeck, *Bull. Mus. Roy. Bruxelles*, ii. (1883), p. 341 ; A. Rutot, *op. cit.* p. 41.

Groups of Strata.—Passing from individual strata to large masses of stratified rock, the geologist finds it needful for convenience of reference to subdivide these into groups. He avails himself of two bases of classification—(1) lithological character, and (2) organic remains.

1. The subdivision of stratified rocks into groups according to their mineral aspect is an obvious and easily applied classification. Moreover, it often serves to connect together rocks formed continuously in certain circumstances which differed from those under which the strata above and below were laid down—so that it expresses natural and original subdivisions of strata. In the middle of the English Carboniferous system of rocks, for example, a zone of sandy and pebbly beds occurs, known as the Millstone Grit. No abrupt and sharp line can be drawn between these strata and those above and below them. They shade upward and downward into the beds between which they lie. Yet they form a conspicuous belt, traceable for many miles by the scenery to which it gives rise. Again, the red rocks of central England, with their red sandstones, marls, rock-salt, and gypsum, form a well-marked group, or rather series of groups. It is obvious, however, that characters of this kind, though sometimes wonderfully persistent over wide tracts of country, must be at best but local. The physical conditions of deposit must always have been limited in extent. A group of strata, showing great thickness in one region, will be found to die away as it is traced into another. Or its place is gradually taken by another group which, even if geologically contemporaneous, possesses totally different lithological characters. Just as at the present time a group of sandy deposits gradually gives place along the sea-floor to others of mud, and these to others of shells or of gravel, so in former geological periods, contemporaneous deposits were not always lithologically similar. Hence mere resemblance in mineral aspect cannot usually be regarded as satisfactory evidence of contemporaneity, except within comparatively contracted areas. The Carboniferous Limestone has already (p. 517) been cited as a notable example. Typically in Belgium, central England, and Ireland, it is a thick calcareous group of rocks, full of corals, crinoids, and other organisms, which bear witness to the formation of these rocks in the open sea. But traced into the north of England and Scotland, it passes into sandstones and shales, with numerous coal-seams, and only a few thin beds of limestone. The soft clay beneath the city of London is represented in the Alps by hard schists and contorted limestones. We conclude, therefore, that lithological agreement, when pushed too far, is apt to mislead us, partly because contemporaneous strata often vary greatly in lithological character, and partly because the same lithological characters may appear again and again in different ages. By trusting too implicitly to this kind of evidence, we may be led to class together rocks belonging to very different geological periods, and, on the other hand, to separate groups which really, in spite of their seeming distinction, were formed contemporaneously.

2. It is by the remains of plants and animals imbedded among the stratified rocks that the most satisfactory subdivisions of the geological record can be made, as will be more fully stated in Books V. and VI.

A chronological succession of organic forms can be made out among the rocks of the earth's crust. A certain common facies or type of fossils is found to characterise particular groups of rocks, and to hold true even though the lithological constitution of the strata should greatly vary. Moreover, though comparatively few species are universally diffused, they possess remarkable persistence over wide areas, and even when they are replaced by others, the same general facies of fossils remains. Hence the stratified formations of two countries geographically distant, and having little or no lithological resemblance to each other, may be compared and paralleled simply by means of their enclosed organic remains.

Order of Superposition—the Foundation of Geological Chronology.—As sedimentary strata were laid down upon one another in a more or less nearly horizontal position, the underlying beds must be older than those which cover them. This simple and obvious truth is termed the Law of Superposition. It furnishes the means of determining the chronology of rocks; and though other methods of ascertaining this point are employed, they must all be based originally upon the observed order of superposition. The only case where the apparent superposition may be deceptive is when the strata have been inverted, as in the Alps (pp. 540, 541), where the rocks composing huge mountain masses have been so completely overturned that the highest beds appear as if regularly covered by others which ought properly to underlie them. But these are exceptional occurrences, wherein the true order can usually be made out from other sources of evidence.

PART II. JOINTS.

All rocks are traversed more or less distinctly by vertical or highly inclined divisional planes termed Joints.[1] Soft rocks, indeed, such as loose sand and uncompacted clay, do not show these lines; but where a sedimentary mass has acquired some degree of consolidation, it usually shows them more or less distinctly. It is by means of the intersection of joints that rocks can be removed in blocks; the art of quarrying consists in taking advantage of these natural planes of division. Joints differ in character according to the nature of the material which they traverse; those in sedimentary rocks are usually distinct from those in crystalline masses.

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[1] M. Daubrée has proposed a classification of the various divisional planes of rocks due to rupture of original continuity, which he groups together as *Lithoclases*. 1. Under the term *Leptoclase* he classes minor fractures, which may be either (*a*) *synclases*, produced by some internal mechanical or molecular action, and generally by contraction, as in cooling and drying; or (*b*) *piësoclases*, produced by some external mechanical movement, particularly by pressure, as in the structures called cone-in-cone, stylolites, and ruiniform marble. 2. *Diaclases* correspond to what in English are called joints. 3. *Paraclases* are faults. *Bull. Soc. Géol. France* (3), x. p. 136. On jointing, faulting, and cleavage in rocks see O. Fisher, *Geol. Mag.* 1884, 204. A. Harker, *Geol. Mag.* 1885, *Brit. Assoc.* 1885, p. 813. G. K. Gilbert, *Amer. Journ. Sci.* xxiii. (1882), p. 25, xxiv. (1882), p. 50, xxvii. (1884), p. 47; W. O. Crosby, *Proc. Boston Soc. Nat. Hist.* xxii. (1882), p. 72, xxiii. p. 243.

1. **In Stratified Rocks.**—To the presence of joints some of the most familiar features of rock-scenery are due (Fig. 225). Joints vary in the angles at which they cut the planes of bedding, in the sharpness of their definition, in the regularity of their perpendicular and horizontal course, in their lateral persistence, in number, and in the directions of their intersection. As a rule, they are most sharply defined in proportion to the fineness of grain of the rock. In limestones and close-grained shales, for example, they often occur so clean-cut as to be invisible until revealed by fracture or by the slow disintegrating effects of the weather. The rock splits up along these concealed lines of division, whether the agent of demolition be the hammer or frost. In coarse-textured rocks, on the other hand, joints are apt to show themselves as more irregular sinuous rents.

As a rule, they run perpendicular, or approximately so, to the planes of bedding, and descend vertically at not very unequal distances, so that the portions of rock between them, when seen in profile, appear marked off into so many wall-like masses. But this symmetry often gives place to a more or less tortuous course with lateral joints in various random directions, more especially where the different strata vary considerably in lithological characters. A single joint may be traced for many yards, sometimes, it is said, for several miles, more particularly when the rock is fine-grained, as in limestone. But where the texture is coarse and unequal, the joints, though abundant, run into each other in such a way that no one in particular can be identified for more than a limited distance. The number of joints in a mass of stratified rock varies within wide limits. Among strata which have undergone little disturbance the joints may be separated from each other by intervals of several yards. But in other cases where terrestrial movement has been considerable, the rocks are so jointed as to have acquired therefrom a fissile character that has nearly or wholly obliterated their tendency to split along the lines of bedding.

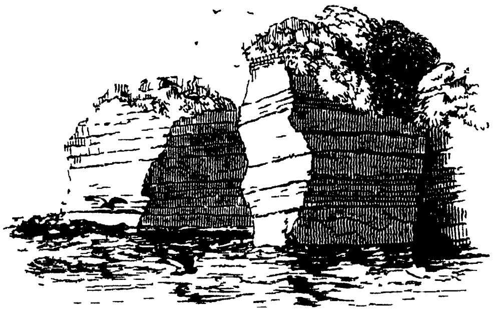

Fig. 225.—Cliffs cut into re-entering angles by lines of Joint (*j*.)
(The faces in shadow are one set of joints, those in light another set.)

An important feature in the joints of stratified rocks is the direction in which they intersect each other. In general they have two dominant trends, one coincident, on the whole, with the direction in which the strata are inclined from the horizon, and the other running transversely at a right angle or nearly so. The former set is known as *dip-joints*, because they run with the *dip* or inclination of the rocks; the latter is termed *strike-joints*, inasmuch as they conform to the *strike* or general outcrop. It is owing to the existence of this double series of joints that ordinary quarrying operations can be carried on. Large quadrangular blocks can be wedged off, which would be shattered if exposed to the risk of blasting. A quarry is usually worked to the dip of a rock; hence the strike-joints form clean-cut faces in front of the workmen as they advance. These are known as "backs," and the dip joints, which traverse them, as "cutters." The way in which this double set of joints occurs in a quarry may be seen in Fig. 226, where the close parallel lines traversing the shaded and unshaded faces mark the planes of stratification, which here are inclined from the spectator. The steep faces in light are defined by the strike-joints or "backs." The faces in shadow have been quarried out along dip-joints or "cutters." It will be observed that the long face in sunlight is cut by parallel lines of dip-joints not yet opened in quarrying, while in like manner, the shaded face to the right, is that of a dip-joint which is traversed by parallel lines of strike-joint.

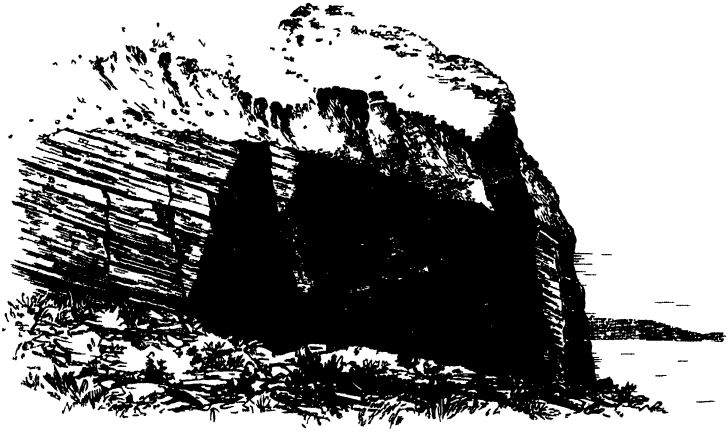

Fig. 226.—Jointing in quarry of Caithness Flags, near Holburn Head.

Ordinary household coal presents a remarkably well-developed system of joints. A block of such coal may be observed to be traversed by fine laminæ, the surfaces of many of which are soft and soil the fingers. These are the planes of stratification. Perpendicular to them run divisional planes, which cut each other at right angles or nearly so, and thus divide the mineral into cubical fragments. One of these sets of joints makes clean sharply defined surfaces, and is known as the *face*, *slyne*, *cleat*, or *bord*; the other has rougher, less regular surfaces, and is known as the *end.* The face remains persistent over wide areas; it serves to define the direction of the roadways in coal-mines, which must run with it.

According to observations made by Jukes, both strike-joints and dip-joints occur in beds of recently-formed coral-rock in the Australian and other reefs.[1] In like manner, a remarkably definite system of jointing has been noticed by Mr. Gilbert in the recent clays and muds of the dried-up bed of the Sevier lake in Utah. Such modern sediments have certainly never been subject to the pressure of any superincumbent rock, nor to the torsion or other disturbance incident to subterranean movement. That great force has sometimes been concerned in the production of the structure is instructively shown in some conglomerates, where the joints traverse the enclosed pebbles, as well as the surrounding matrix, in such a way that large blocks of hard quartz are cut through by them as sharply as if they had been sliced in a lapidary's machine, and the same joints can be traced continuously through many yards of the rock (Fig. 227).[2] Indication of relative movement of the sides of a joint is often supplied by their rubbed and striated surfaces, termed *slickensides*, which have evidently been ground against each other. They are often coated with hæmatite, calcite, chlorite, or other mineral, which has taken a cast of the striæ and then seems itself to be striated.

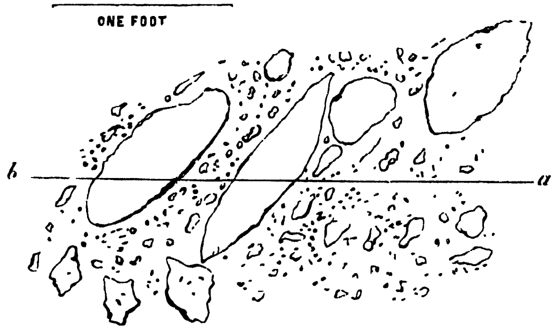

Fig. 227.—Plan of coarse conglomerate of blocks of Cambrian rocks in Carboniferous Limestone, traversed by a line of joint cutting the individual boulders in the line *a b*. Coast near Skerries, Dublin County (B.)

The cause of jointing has not been satisfactorily explained. Various theories have been proposed to account for the structure; but as no one will explain every case, it is probable that what we call joints may have originated in several different ways, or, in other words, that the results of several distinct natural processes are all indiscriminately comprised under the term joint. The following theories may be enumerated.

(1) Contraction.—The contraction of rocks gives rise to fissures of retreat in their mass, whether it results from the drying and consolidation of aqueous sediments or from the cooling of masses that have been

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[1] 'Manual of Geology,' 3rd edition, p. 184.

[2] De la Beche, 'Geol. Observer,' p. 628.

molten or have been highly heated. The prismatic or columnar system of joints observable in the gypsum of the Paris Basin, of which the beds are divided from top to bottom into vertical hexagonal prisms, may be an instance of this cause.[1] A columnar structure has often been superinduced upon stratified rocks (sandstone, shale, coal) by contact with intrusive igneous masses (p. 599).

(2) Crystalline or Magnetic Forces.—Jointing has been regarded as referable to forces analogous to those that have produced the cleavage of minerals, the difference between the two arising perhaps from the forces in the case of jointing being subordinated to terrestrial magnetism, while those concerned in mineral cleavage are obedient to crystalline polarity.[2] But this theory has met with little support.

(3) Compression.—Jointing has been associated by some authors with cleavage as a result of the lateral compression of rocks (p. 312).

(4) Torsion.—From experiments on the behaviour of various substances under the strain of torsion, M. Daubrée concludes that a system of joints may be explained as the results of the torsion of strata arising during the movements to which the crust of the earth has been subjected.[3]

(5) Earthquakes.—The existence of joints has been referred to the results of the earth-waves generated during earthquakes, the rocks through which the waves pass being exposed to such powerful alternate compression and tension as to rupture them.[4]

Joints form natural lines for the passage downward and upward of subterranean water. They likewise furnish an effective lodgment for the action of frost, which wedges off blocks of rock in the manner already described (p. 414). As they serve, in conjunction with bedding, to divide stratified rocks into large quadrangular blocks, their influence in the weathering of these rocks is seen in the symmetrical and architectural as well as splintered, dislocated aspects so familiar in the scenery of sandstone and limestone districts.

2. **In Massive (Igneous) Rocks.**—While in stratified rocks, the divisional planes consist of lines of bedding and of joint, cutting each other usually at a high, if not a right angle; in massive (igneous) rocks, they include joints only; and as these do not, as a rule, present the same parallelism as lines of bedding, unstratified rocks, even though as full of joints, have not the regularity of arrangement of stratified formations. Some massive rocks indeed may have one system of divisional planes so largely developed as to acquire a bedded or fissile character. This structure, characteristically shown by phonolites, may also be detected among ancient porphyries (Fig. 228). Most massive rocks are traversed by two intersecting sets of chief or "master" joints, whereby the rock is divided into long quadrangular, rhomboidal, or even polygonal columns. A third set may usually be noticed cutting across the columns and

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[1] Jukes's 'Manual,' 3rd edition, p. 180.

[2] Prof. W. King, *Trans. Roy. Irish Acad.* xxv. (1875), p. 641.

[3] 'Etudes de Géologie Expérimentale,' p. 300, and *ante*, p. 318.

[4] W. O. Crosby, *Proc. Boston Soc. Nat. Hist.* xxii. (1882), p. 72.

articulating them into segments, though generally less continuous and dominant than the others (Fig. 229). When these last-named cross-joints are absent or feebly developed, columns many feet in length can be quarried out entire. Such monoliths have been from early times employed in the construction of obelisks and pillars.

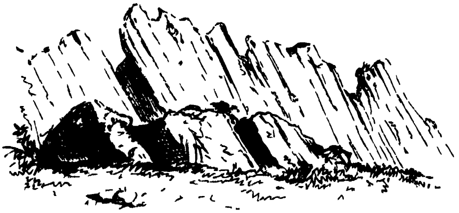

Fig 228.—Porphyry, near Clynog Vawr, Caernarvonshire, divided into slabs by a system of close parallel joints (*B.*)

In large masses of granite, an outward inclination of the natural divisional planes of the rock may sometimes be observed, as if the granite were really a rudely bedded mass, having a dip towards and under the strata which rest upon its flanks. It is not a foliated arrangement of the constituent minerals analogous to the foliation of gneiss, for it can be traced in perfectly amorphous and thoroughly crystalline granite, but is undoubtedly a form of jointing by reason of which the rock weathers into large blocks piled one upon another like a kind of rude cyclopean masonry.[1] In the quarrying of granite, the workmen recognise that the rock splits into blocks much more easily in one direction, though externally there is no trace of any structure which could give rise to this tendency.

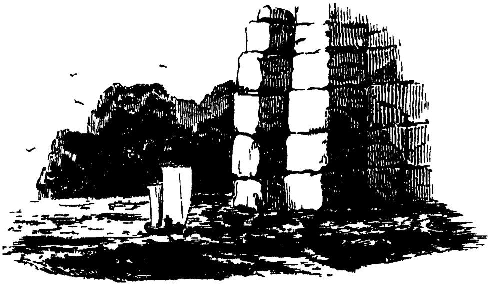

Fig 229.—Jointed structure of Granite.

Rocks of finer grain than granite, such as many diorites and dolerites, acquire a prismatic structure from the number and intersection of perpendicular joints. The prisms, however, are unequal in dimensions, as well as in the number and proportions of their sides, a frequent diameter being 2 or 3 feet, though they may sometimes be observed three times thicker, and extending up the face of a cliff for 300 or 400 feet. It is by means of joints that precipitous faces of crystalline, no less than of sedimentary rock are produced and maintained, for they serve as openings into which frost drives every year its wedges of ice. They likewise give rise to the formation of the fantastic pinnacles and fretted buttresses characteristic of massive rocks.

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[1] In the granite of the axes of the Rocky Mountains and parallel ranges to the westward, a kind of bedded structure has been described as passing under the crystalline schists.

As lava, erupted to the surface, cools and passes into the solid condition, a contraction of its mass takes place. This diminution of bulk is accompanied by the development of divisional planes or joints, more especially diverging from the upper and under surfaces, and intersecting at irregular distances, so as to divide the rock into rude prisms. Occasionally another series of joints, at a right angle to these, traverses the mass, parallel with its upper and under surfaces, and thus the rock acquires a kind of fissile or bedded appearance. The most characteristic structure, however, among volcanic rocks is the prismatic, or, as it is incorrectly termed "basaltic." Where this arrangement occurs, as it so commonly does in basalt, the mass is divided into tolerably regular pentagonal, hexagonal, or irregularly polygonal prisms or columns, set close together at a right angle to the main cooling surfaces (Fig. 230). These prisms vary from 1 inch or even less to 18 or more inches in diameter, and range up to 100 or even 150 feet in height. Many excellent and well-known examples of columnar structure are exhibited on the coast-cliffs of the Tertiary volcanic region of Antrim and the west of Scotland, as in the Giant's Causeway and Fingal's Cave. In many cases, no sharp line can be drawn between a columnar basalt and the beds above and below, which show no similar structure, but into which the prismatic mass seems to pass.

Considerable discussion has arisen as to the mode in which this columnar structure has been produced. That it is a species of jointing, due to contraction, was long ago pointed out by Scrope, and is now generally conceded, though the conditions under which it is produced are not quite clear.[1] Prof. James Thomson showed how the columnar structure might be explained as a phenomenon of contraction, and subsequently Mr. Mallet concluded that "all the salient phenomena of the prismatic and jointed structure of basalt can be accounted for upon the admitted laws of cooling, and contraction thereby, of melted rocks possessing the known properties of basalt, the essential conditions being a very general homogeneity in the mass cooling, and that the cooling shall take place slowly, principally from one or more of its surfaces." In the more perfectly columnar basalts, the columns are sometimes articulated, each prism being separable into vertebræ, with a cup-and-ball socket at each articulation (Figs. 231 and 232). This peculiarity was traced by Mr. Mallet to the contraction of each prism in its length and in its diameter, and to the consequent production of transverse joints, which, as the resultant of the two contracting strains, are oblique to the sides of the prism, but, as the obliquity lessens towards the centre, assume necessarily when perfect, a cup-shape, the convex surface pointing in the same direction as that in which the prism has grown. This explanation, however, will hardly account for cases, which are not uncommon, where the convexity points the other way, or where it is sometimes in one direction and sometimes in the other.[1] The remarkable spheroids (Fig. 94) which appear in many weathered igneous rocks besides basalts may be due, where they are not the result of weathering, to continued contraction within the hexagonal or polygonal spaces defined by the columnar joints and cross-joints of a cooling mass. The contraction of these blocks would tend to the development of successive spheroidal shells, which might remain mutually adherent and invisible in a fresh fracture of the rock, yet might make their presence effective during the complex processes of weathering.[2] After some exposure, the spheroids of basalt begin to appear, and gradually crumble away by the successive formation and disappearance of external weathered crusts or coats, which fall off into sand and clay. Almost all augitic or hornblendic rocks, with many granites and porphyries, exhibit the tendency to decompose into rounded spheroidal blocks. The columnar structure, though abundant among modern volcanic rocks, is by no means confined to these. It is as well displayed among the lavas of the Lower Old Red Sandstone, and of the Carboniferous Limestone in central Scotland, as among those of Tertiary age in Auvergne or the Vivarais.

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[1] G. P. Scrope, 'Geology and Extinct Volcanoes of Central France,' p. 92. J. Thomson, *Brit. Assoc.* 1863, sects. p. 95. R. Mallet, *Proc. Roy. Soc.* 1875; *Phil. Mag.* ser. 4, vol. i. pp. 122, 201. T. G. Bonney, *Q. J. Geol. Soc.* 1876, p. 140. J. Walther, *Jahrb. Geol. Reichsanst.* 1886, p. 295. J. P. Iddings, *Amer. Journ. Sci.* xxxi. (1886), p. 321.

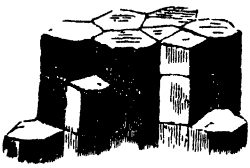

Fig. 230.—Ordinary columnar structure of Lava.

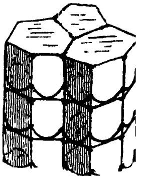

Fig. 231.—Ball-and-socket Jointing of columns.

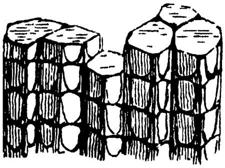

Fig. 232.—Modification of ball and-socket structure.

As already stated, prismatic forms have been superinduced upon rocks by a high temperature and subsequent cooling, as where coal and sandstone have been invaded by basalt. They may likewise be observed to arise during the consolidation of a substance from aqueous solution. In starch, for example, the columnar structure may be well developed, and not infrequently radiates from certain centres, as in basalt and other igneous rocks.

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[1] Mr. Scrope pointed this out (*Geol. Mag.* September 1875), though Mr. Mallet (*ibid.* November 1875) replied that in such cases the articulations must be formed just about the dividing surface, between the part of the rock which cooled from above and that which cooled from below. See also on this subject J. P. O'Reilly, *Trans. Roy. Irish Acad.* xxvi. (1879), p. 641.

[2] Bonney, *Q. J. Geol. Soc.* 1876, p. 151. The perlitic structure is probably a microscopic example of the same kind of contraction.

3. **In Foliated (Schistose) Rocks.**—The schists likewise possess their joints, which approximate in character to those among the massive igneous rocks, but they are on the whole less distinct and continuous, while their effect in dividing the rocks into oblong masses is considerably modified by the transverse lines of foliation. These lines play somewhat the same part as those of stratification among the stratified rocks, though with less definiteness and precision. The jointing of the more massive foliated rocks, such as the coarser varieties of gneiss, approaches most closely to that of granite; in the finely fissile schists, on the other hand, it is rather linked with that of sedimentary formations. Upon these differences much of the characteristic variety of outline presented by cliffs and crests of foliated rocks depends.

PART III. INCLINATION OF ROCKS.

The most casual observation is sufficient to satisfy us that the rocks now visible at the earth's surface are seldom in their original position. We meet with sandstones and conglomerates composed of water-worn particles, yet forming the angular scarps of lofty mountains; shales and clays full of remains of fresh-water shells and land-plants, yet covered by limestones made up of marine organisms, and these limestones rising into great ranges of hills, or undulating into fertile valleys, and passing under the streets of busy towns. Such facts, now familiar to every reader, and even to many observers who know little or nothing of systematic geology, point unmistakably to the conclusion that most of the rocks of the land have been formed under water, sometimes in lakes, more frequently in the sea, and that they have been elevated into land.

But further examination discloses other and not less convincing evidence of movement. Judging from what takes place at the present time on the bottoms of lakes and of the sea, we confidently infer that when the strata now constituting so much of the solid framework of the land were formed, they were laid down nearly horizontally, or at least at low angles (*ante*, p. 501). When, therefore, we find them inclined at all angles, and even standing on end, we conclude that they have been disturbed. Over wide spaces, they have been upraised bodily, with little alteration of horizontality; but in most places some departure from that original position has been effected.

Dip.—The inclination thus given to rocks is termed their Dip. Its amount is expressed in degrees measured from the plane of the horizon. Thus a set of rocks half-way between the horizontal and vertical position would be said to dip at an angle of 45°, while if vertical they would be marked with the angle of 90°. The inclination is measured with an instrument termed the Clinometer, which is variously made, but of which one of the simplest forms is shown in Fig. 233. This consists of a thin strip of boxwood, two inches broad, strengthened with brass along the edges, and divided into two leaves, each 6 inches long, hinged together so that when opened out they form a foot-rule. On the inside of one of these leaves, a graduated arc with a pendulum is inserted. When the instrument is held horizontally, the pendulum points to zero. When placed vertically, it marks 90°. By retiring at a right angle to the direction of dip of a group of inclined beds, and holding the clinometer

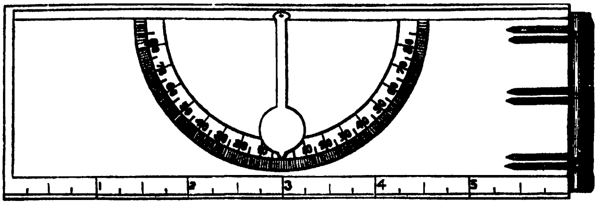

Fig. 233.—Clinometer—the leaf containing the pendulum and index. (Half the size of the original.)

before the eye until its upper edge coincides with the line of bedding, we readily obtain the amount or angle of dip. In observations of this nature it is of course necessary either to place the clinometer strictly parallel with the direction of dip, or, if this be impossible, to take two measurements, and calculate from them the true angle.[1] Simple as observation of dip is, it is attended with some liabilities to error, against which the observer should be on his guard. A single face of rock may not disclose the true dip, especially if it be a clean-cut joint-face. In Fig. 234, for example, the strata might be supposed to be horizontal, but another side view of them (as Fig. 235) might show them to be gently inclined or even nearly vertical.

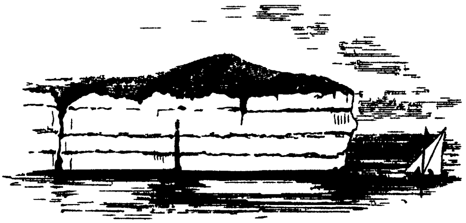

Fig. 234.—Apparently horizontal strata (*B.*)

Again, a deceptive surface inclination is not infrequently to be seen among thin-bedded strata. Mere gravitation, aided by the downward pressure of sliding detritus or "soil-cap," suffices to bend over the edges of fissile strata, which, though really dipping into the hill, are thus made to appear superficially to dip away from it (Fig. 236). Similar effects, with even proofs of contortion, may be noticed under boulder clay, or in other situations where the rocks have been bent over and crushed by a mass of ice.

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[1] In Jukes' 'Memoir on the South Staffordshire Coal-Field,' in *Memoirs of Geol. Survey* (2nd edit. p. 213), a formula is given for calculating the true dip from the apparent dip seen in a cliff. A graphical method of computing the true dip from observations of two apparent dips has been suggested by Mr. W. H. Dalton, *Geol. Mag.* x. p. 332. See also Green's 'Physical Geology,' 1882, p. 460. A. Harker, *Geol. Mag.* 1884, p. 154.

When the dip is outward in every direction from a central point, it is said to be *quâ-quâ-versal* (A in Fig. 238). Strata thus affected are thrown into a dome-shaped structure, while when the dip is towards a central point, they have a basin-shaped structure.

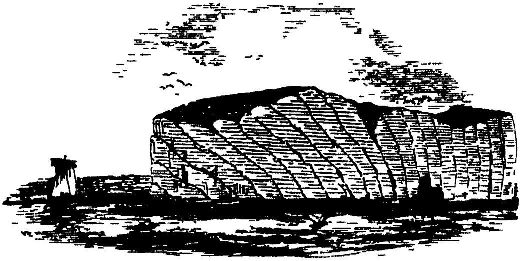

Fig. 235.—Real inclination of strata shown in Fig. 234 (*B.*)

Outcrop.—The edges of strata which appear at the surface of the ground are termed their Outcrop or Basset. If the strata are quite horizontal, the direction of outcrop depends on inequalities of the ground and variations in amount of denudation. Perfectly level ground lying upon horizontal beds shows, of course, no outcrop, for the surface coincides with a plane of stratification. But occasional water-courses have been eroded below the general level, so as to reveal along their sides outcrops of the strata. The remarkable sinuosities of outcrop produced by the unequal erosion of horizontal strata are illustrated in Fig. 237, where A is a map of a piece of ground deeply trenched by valleys, and B that of an area comparatively little denuded. In both cases the outcrops are seen to wind round the sides of the slopes.

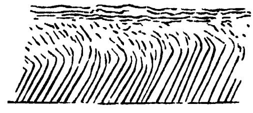

Fig. 236.—Deceptive superficial dip.

Where strata are inclined, the course of their outcrop is regulated partly by the direction and amount of inclination, and partly by the form of the ground. When with low angles of dip they *crop out*, that is, rise to the surface, along a perfectly level piece of ground, the outcrop runs at a right angle to the dip. But any inequalities of the surface, such as valleys, ravines, hills, and ridges, will, as in the case of horizontal beds, cause the outcrop to describe a circuitous course, even though the dip should remain perfectly steady all the while. If a line of precipitous gorge should run directly with the dip, the outcrop will there be coincident with the dip. The occurrence of a gently shelving valley in that position will cause the outcrop to descend on one side and to mount in a corresponding way on the other, so as to form a V-shaped indentation in its course. A ridge, on the other hand, will produce a deflection in the opposite direction. Hence a series of parallel ridges and valleys, running in the same direction as the dip of the strata underneath, causes the outcrop to describe a widely serpentinous course.

The breadth of the outcrop depends on the thickness of the stratum and on the angle of dip. A bed one foot thick inclined at an angle of 1°, on a perfectly level piece of ground would have an outcrop about 60 feet broad. At a dip of 5° the breadth of the outcrop would be a little over 11 feet. At 30° it would be reduced to 2 feet, and the diminution would continue until, when the bed was on end, the breadth of the outcrop would, of course, exactly correspond with the thickness of the bed. It is further to be observed that among vertical rocks, the direction of the outcrop necessarily corresponds with the strike, and continues to do so irrespective altogether of any irregularities of the ground. The lower therefore the angle of inclination, the greater is the effect of surface-inequalities upon the line of outcrop; the higher the angle, the less is that influence, till when the beds stand on end it ceases.

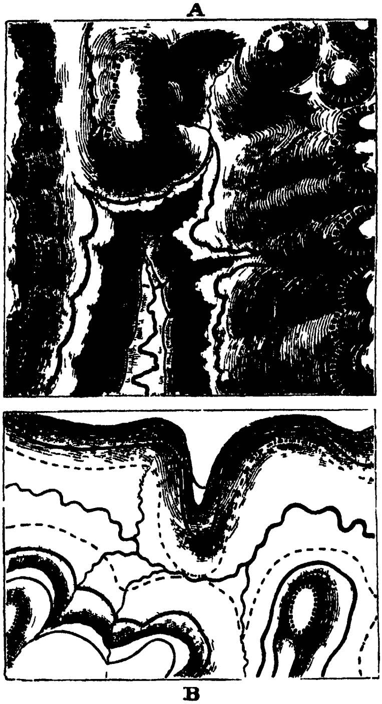

Fig 237 —Sinuous outcrops of horizontal strata depending on inequalities of surface
The wavy black lines mark the outcrops of successive conformable horizontal beds.

Strike.—A horizontal line drawn at a right angle to the dip is called the Strike of the rocks. From what has just been said, this line must coincide with outcrop when the surface of the ground is quite level, as on the beach in Fig. 238, and also when the beds are vertical. At all other times, strike and outcrop are not strictly coincident, but the latter wanders to and fro across the former according to changes in the contour of the ground. The strike may be a straight line, or may curve rapidly in every direction, according to behaviour of the dip. A set of beds dipping westwards for half a mile (*a* to *b*, Fig. 238) have a north and south strike for the same distance. If the dip changes to S.W., S., S.E., and E., the strike will bend round in a curving line (as at S). In the case of a *quâ-quâ-versal* dip the strike forms a complete circle (as at A) The dip being ascertained gives the strike, but the strike does not certainly indicate the direction of dip, which may be either to the one side or the other. Two groups of strata, dipping the one east and the other west, have both a north and south strike. Strike may be conceived as always a level line on the plane of the horizon, so that, no matter how much the ground may undulate, or the outcrop may vary, or the dip may change, the strike will remain horizontal. Hence in mining operations, it is commonly spoken of as the *level-course* or *level-bearing.* A "level" or underground roadway, driven through a coal-seam at right angles to the dip, will undulate in its trend if the dip changes in direction, but it may be made perfectly level, and kept so throughout a whole coal-field so long as it is not interfered with by dislocations.

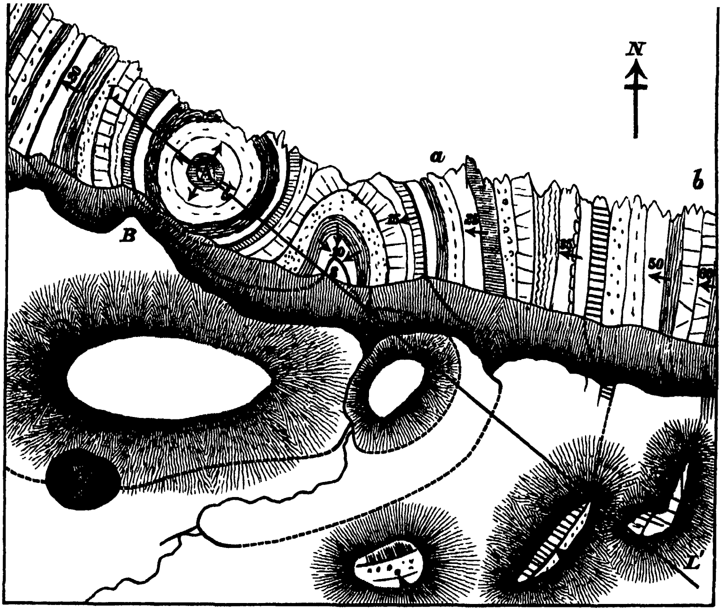

Fig. 238.—Geological Map, showing strata exposed continuously along a beach and occasionally in the interior.

In Fig. 238, the strike and outcrop are coincident on the flat beach, but cease to be so the moment the ground begins to slope up into the coast-cliff. This is seen in the eastern half of the map, where the lines of outcrop slant up into the cliff at an angle dependent mainly on the amount of the dip. A section drawn in the line L L′ would show the geological structure represented in Fig. 239. By noting the angles of dip it is possible to estimate the thickness of a series of beds, and how far beneath the surface any given bed might be expected to be found. If, for instance, the horizontal distance across the strike between beds S and A (Fig. 238) were found to be 200 feet, with a mean dip of 15°, the actual thickness would be 51·8 feet, and bed A would be found at a depth of 53·8 feet below the outcrop of S. If the same development of strata continues inland, the bed *a* should be found at a little more than 200 feet beneath the surface, if a

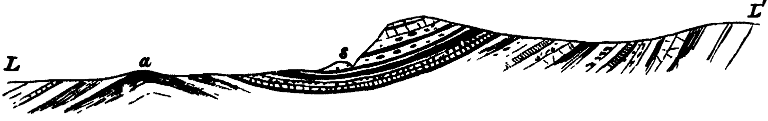

Fig. 239.—Section along the line L L′ in Fig. 238.

bore were sunk to it in the quarry (Q). If the total depth of rock between *a* and *b* be 1000 feet, then evidently, if the strata could be restored to their original approximately horizontal position, with bed *a* at the surface, bed *b* would be covered to a depth of 1000 feet. It will be noticed also that as the angle of dip increases, the outcrops are thereby brought closer together. Where the outcrops run along the face of a cliff or steep bank (B) they must likewise be drawn together on a map. In reality, of course, these variations take place though the same vertical thickness of rock may everywhere intervene between the several outcrops.

It is usually desirable to estimate the thicknesses of strata, especially where, as in Fig. 239, they are exposed in continuous section. A convenient though not strictly accurate rule for this purpose may be applied in cases where the angle of inclination is less than 45°. The real thickness of a mass of inclined strata may be taken to be $\frac{1}{12}$ of its apparent thickness for every 5° of dip. Thus if a set of beds dips steadily in one direction at 5° for a horizontal space of 1200 feet measured perpendicularly to the strike, their actual thickness will be $\frac{1}{12}$, or 100 feet. If the dip be 15°, the true thickness will be $\frac{3}{12}$, or 300 feet, and so on.[1]

PART IV. CURVATURE.[2]

A little reflection will show that though, so far as regards the trifling portions of the rocks visible at the surface, we might regard the inclined surfaces of strata as parts of straight lines, they must nevertheless be parts of large curves. Take for example the section in Fig. 240. At the left hand the strata descend beneath the surface at an angle of no more than 15°, but at the opposite end the angle has risen to 60°. There being no dislocation or abrupt change of inclination, it is evident that the beds cannot proceed indefinitely downward at the same angle which they have at the surface, otherwise they would run away from each other, but must bend round to accommodate themselves to the difference of inclination. By prolonging the lines of bedding for some way beneath and above sea-level, we can show graphically that the strata are necessarily curved (Fig. 241). A section of this kind brings out clearly the additional fact that an upward continuation of the curved beds must have been carried away by the denudation of the surface. In every instance therefore where, in walking over the surface, we traverse a series of strata which gradually, and without dislocations, increase or diminish in inclination, we cross part of a curvature in the strata of the earth's crust. The foldings, however,

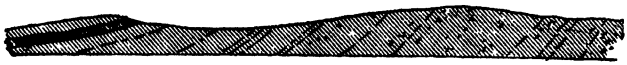

Fig. 240.—Section of inclined strata.

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[1] Maclaren's 'Geology of Fife and the Lothians,' 2nd edit. p. xix. For tables for estimating dip and thickness see Jukes' 'Manual,' p. 748; Green's 'Physical Geology,' p. 460.

[2] A useful compendium of information regarding geological terms for the dislocations and curvatures of rocks has been prepared by M. E. de Marjerie and Professor A. Heim, 'Les dislocations de l'écorce terrestre,' 1888, Zurich (in French and German).

can often be distinctly seen on cliffs, coast-lines, or other exposures of rock (Fig. 242). The observer cannot long continue his researches in the field without discovering that the strata composing the earth's outer crust

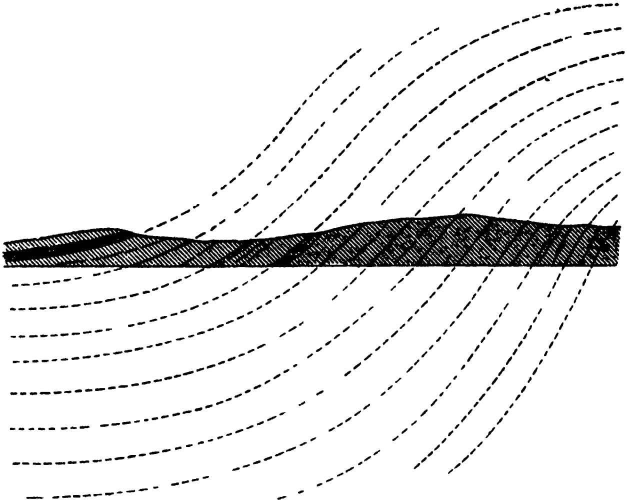

Fig 241.—Section of inclined strata, as in Fig 240, showing that they form part of a large curve

have been almost everywhere thrown into curves, usually so broad and gentle as to escape observation except when specially looked for.

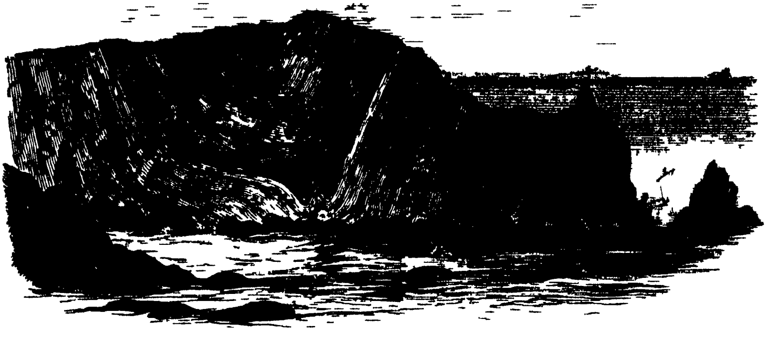

Fig. 242.—Curved Silurian rocks on the Coast of Berwickshire

If the inclination and curvature of rocks are so closely connected, a corresponding relation must hold between their strike and curvature In fact, the prevalent strike of a region is determined by the direction of the axes of the great folds into which the rocks have been thrown. If the curves are gentle and inconstant, there will be a corresponding variation in the strike. But should the rocks be strongly plicated, there will necessarily be the most thorough coincidence between the strike and the direction of the plication.

Monoclines.—Curvature occasionally shows itself among horizontal or gently inclined strata in the form of an abrupt inclination, and then an immediate resumption of the previous flat or gently sloping character. The strata are thus bent up and continue on the other side of the fold at a higher level. Such bends are called Monoclines or monoclinal folds, because they present only one fold, or one-half of a fold, instead of the two in an arch or trough (Fig. 265, section 1). The most notable instance of this structure in Britain is that of the Isle of Wight (Fig. 243), where the Cretaceous rocks (*c*) on the south side of the island rapidly rise in inclination till they become nearly vertical, while the Lower Tertiary strata (*t*) follow with a similar steep dip, but rapidly flatten down towards the north coast. Probably the most gigantic monoclinal folds in the world are those into which the remarkably horizontal and undisturbed rocks of the Western States and Territories of the American Union have been thrown.[1]

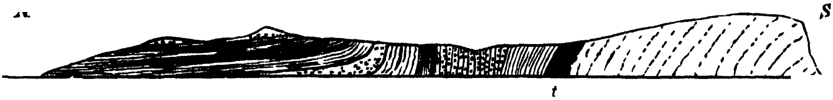

Fig. 243.—Section of a Monoclinal Fold, Isle of Wight.

From the abundance of inclined strata all over the world, we may readily perceive that the normal structure of the visible part of the earth's crust is one of innumerable foldings of the rocks. Sometimes more steeply, sometimes more gently undulated, not infrequently dislocated and displaced, the sedimentary accumulations of former ages everywhere reveal evidence of great internal movement. Here and there, the movement has resulted in the formation of a dome-shaped elevation of the strata, wherein, as if pushed up from a single point, they slope away on all sides from the centre of greatest upthrust, with a *quâ-quâ-versal* dip. Where the top of the dome has been removed, the successive outcrops of the strata form concentric rings, the lowest at the centre, the highest at the circumference (A in Figs. 238 and 239).

Anticlines and Synclines.—But in the vast majority of cases, the folding has taken place, not round a point but along an axis. Where strata dip away from an axis so as to form an arch or saddle, the structure is termed an Anticline, or anticlinal axis (Fig. 244). Where they dip towards an axis, forming a trough or basin, it is called a Syncline, or synclinal axis (Fig. 245). An anticlinal or synclinal axis must always die out unless abruptly terminated by dislocation. In the case of the anticline, the axis, after continuing horizontal, or but slightly inclined, at last begins to turn downward, the angle of inclination lessens, and the arch then ends or "noses out." In a syncline, the axis eventually bends upward, and the beds, with gradually lessening angles, swing round it. In a symmetrical anticline or syncline, the angle of slope is the same or nearly so on either side (Figs. 244, 245). But a difference of inclination is frequently to be observed. The Appalachian coal-field, for example, as shown by H. D. and W. B. Rogers, presents an instructive series of plications, beginning with symmetrical folds, succeeded by others with steep fronts towards the west, until at last these steeper fronts pass under the opposite sides of the arches, giving rise to a series of inverted folds (Fig. 246).

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[1] See Powell's 'Exploration of the Colorado River of the West,' and 'Geology of the Uinta Mountains,' in the Reports of the United States Geographical and Geological Survey. Dutton's 'High Plateaux of Utah,' and 'History of the Grand Cañon'; Gilbert's 'Geology of the Henry Mountains.' Compare Richthofen's 'China,' vol. ii.

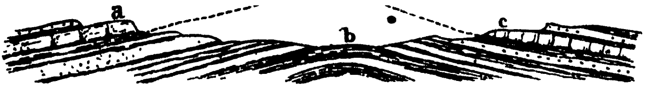

Fig. 244.—Arch, or Anticline, which has been denuded by the removal of beds, as shown by the dotted line *a c* above the axis *b*.

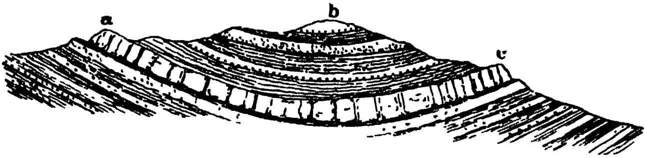

Fig. 245.—Trough, or Syncline, with strata (*a c*) rising from each side of a central axis (*b*).

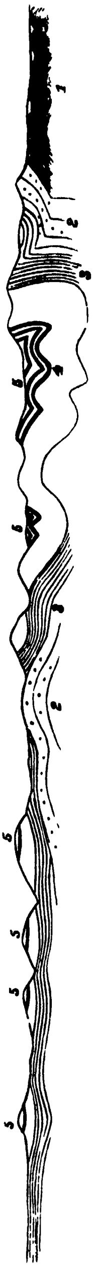

Fig. 246.—Section across the folded rocks of the Appalachian Chain (H. D. Rogers).

Inversion.—Inverted folds occur abundantly in regions of great plication. The Silurian uplands of the south of Scotland, for instance, have the arches and troughs tilted in one direction for miles together, so that in one-half of each of them the strata lie bottom upwards (Fig. 247).[1] It is in large mountain-chains, however, that inversion can be seen on the grandest scale. The Alps furnish numerous striking illustrations. On the north side of that chain, the Secondary and Tertiary rocks have been so completely turned over for many miles that the lowest beds now form the tops of the hills, while the highest lie deep below them. Individual mountains, such as the Glärnisch and some in the

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[1] Prof. Lapworth has worked out with much skill the inverted anticlines and synclines of the "Moffat Shales" (*Q. J. Geol. Soc.* xxxiv. (1878), p. 240); and see also his papers on the "Secret of the Highlands" (*Geol. Mag.* 1883).

Cantons Glarus and St. Gall (Figs. 248, 249), present stupendous examples of inversion, great groups of strata being folded over and over each other as we might fold carpets.[1]

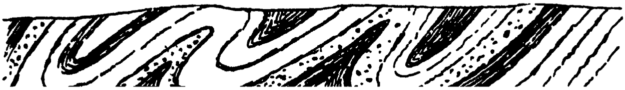

Fig. 247.—Inverted Folds and Isoclinal Structure.

Where a series of strata has been so folded and inverted that its reduplicated members appear to dip regularly in one direction, the structure is termed **isoclinal**. This structure, illustrated on a small scale among the curved Silurian rocks shown in Fig. 247, occurs on a grand scale among the Alps, where the folds have sometimes been so squeezed together that, when the tops of the arches have been worn away, the strata could scarcely be supposed to have been really inverted, save for the evidence as to their true order of succession supplied by their included fossils. The extent of this compression in the Alps has been already (p. 317) referred to.[2] So intense has been the plication, and so

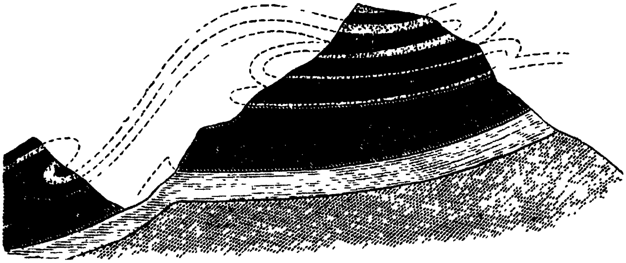

Fig. 248.—Inversion in the Glarnisch Mountain (Baltzer).

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[1] The Glarner double fold has been the subject of considerable discussion. According to Heim ('Mechanismus der Gebirgsbildung') the whole of the rocks, schists included, remained undisturbed until the time of the post-eocene folding. Vacek, however, contends, with evident probability, that the older schists are unconformably overlain by later formations. See M. Vacek, *Jahrb. Geol. Reichsanst.* 1879, p. 726; 1884, pp. 233, 620; *Verhandl. Geol. Reichs.* 1880, p. 189; 1881, p. 43. A. Heim, *Verhandl. Geol. Reichs.* 1880, p. 155; 1881, p. 204. See also *Arch. Sci. Phys. Nat.* Geneva, November 1882, p. 24; Lory, *Bull. Soc. Géol. France*, 3me sér. xi. (1882), p. 14. In Fig. 249, no mere plication could bring the White Jura where it lies comparatively undisturbed on the edge of the excessively plicated Eocene beds. It has evidently been pushed over the latter, the line of junction between them being a "thrust-plane" (p. 551).

[2] See also F. M. Stapff, 'Zur Mechanik der Schichtenfaltungen,' *Neues Jahrb.* 1879, pp. 292, 792. A fine series of sections illustrating the various features of mountain structure may be found in the plates accompanying the 'Matériaux pour la Carte Géologique de la Suisse.' See especially Livraison xvi. on the *Vaudois Alps* by Prof. Renevier; Livraison xxi. by E. Favre and Schardt, on *Canton de Vaud*, &c., and xxv. by A. Heim on the *High Alps between Reuss and Rhine.* An interesting study of an abnormal system of folds and

great the subsequent denudation, that portions of Carboniferous strata appear as if regularly interbedded among Jurassic rocks, and indeed could not be separated save after a study of their enclosed organic remains.

A further modification of the folded structure is presented by the fan-shaped arrangement (*structure en éventail, Facher-Falten*) into which highly plicated rocks have been thrown. The most familiar example is that of Mont Blanc, where the sedimentary strata at high angles seem to dip under the crystalline schists (Fig. 249).

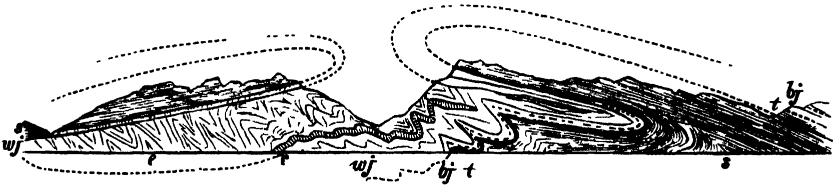

Fig. 249.—Inversion and Thrust-plane among the mountains south of the Lake of Wallenstadt, Cantons Glarus and St. Gall (A Heim).

e, Eocene; *c*, Cretaceous; *w.j.* White Jura thrust upward on the left hand over the plicated Eocene; *b.j.* Brown Jura; *t*, Trias; *s*, Schistose rocks, perhaps metamorphosed Palæozoic formations.

Crumpling.—In the general plication of a district there are usually localities where the pressure has been locally so intensified that the strata have been corrugated and crumpled, till it becomes almost impossible to follow out any particular bed through the disturbed ground. On a small scale, instances of such extreme contortion may now and then be found at faults and landslips, where fissile shales have been corrugated by subsiding heavy masses of more solid rock (Fig. 251). But it is, of course, among the more plicated parts of mountain-chains that the structure receives its best illustrations. Few travellers who have passed the upper end of the Lake of Lucerne can have failed to notice the remarkable cliffs of contorted rocks near Fluelen. But innumerable examples of equal or even superior grandeur may be observed among the more preci-

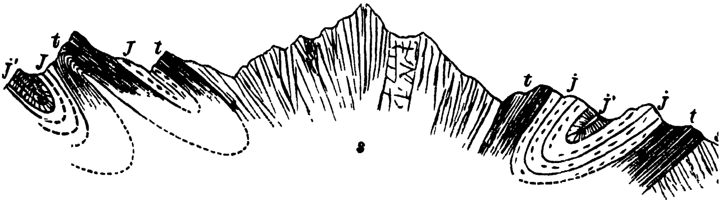

Fig. 250.—Fan-shaped structure, Central Alps.

j', Upper Jurassic Limestone; *j*, Brown Jura and Lias; *t*, Trias; *s*, Schistose rocks.

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faults involving Triassic, Jurassic, and Cretaceous rocks in the south of France, will be found in M. Bertrand's monograph, 'Le Massif d'Allauch,' *Bull. Carte Géol. France*, iii. No. 24 (1891), p. 283.

pitous valleys of the Swiss Alps. Striking illustrations of the same structure may be found in any great mountain chain (Fig. 252). No more impressive testimony could be given to the potency of the force by which mountains were upheaved. And yet, striking as are these colossal examples, involving as they do whole mountain masses in their folds, their effect upon the mind is even heightened when we discover that such has been the strain to which solid limestones and other rocks have been subjected that even their finer layers have been intensely puckered. Some

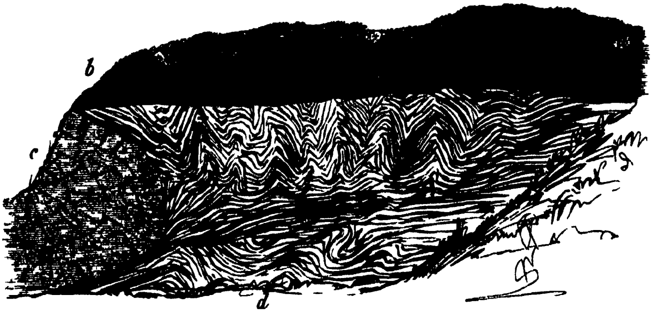

Fig 251.—Locally crumpled strata near a fault, Dalquharran, Ayrshire
d, Shales, *c*, Limestone, *b*, Boulder clay

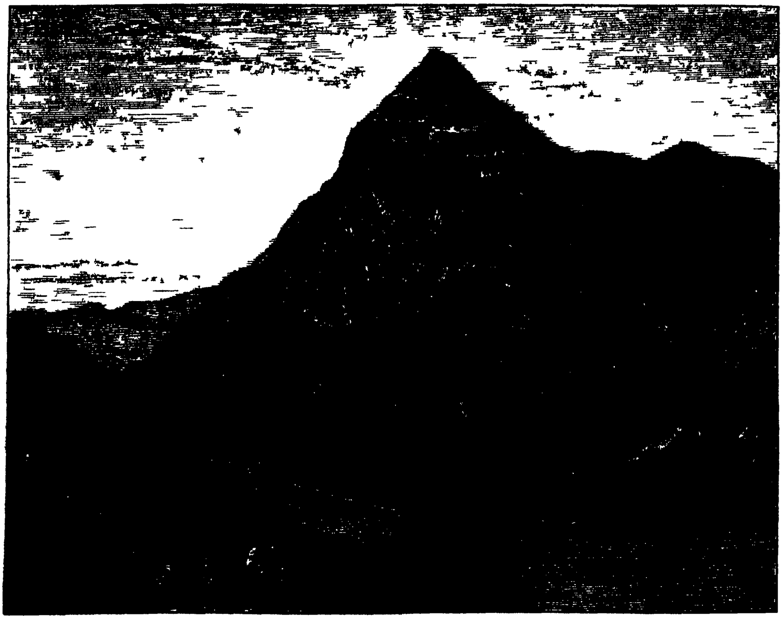

Fig. 252.—Contorted Rocks, east end of Lake Minnewonka, Banff, Canadian Pacific Railway

of these minor crumplings are readily visible to the eye in hand-specimens (Figs. 36, 253, 254). But in many foliated, crumpled rocks the puckering is so minute as to be best seen with the microscope (Fig. 37). Frequently the puckerings have been ruptured and a fine cleavage or jointing has been produced (Ausweichungsclivage, strain-slip cleavage).

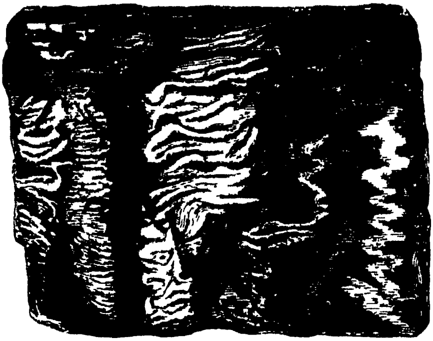
Fig. 253.—Piece of Alpine limestone, showing fine puckering produced by great lateral compression (real size).

It may often be observed that in strata which have been intensely crumpled, the same bed is reduced to the smallest thickness in the arms of the folds, but swells out at the bends as if squeezed laterally into these loops. This appearance, so noticeable in mountain structure, may be seen on lower grounds, as in Pembrokeshire, where De la Beche has shown that the roofs and pavements of coal-seams are brought together, the coal itself, as having least resistance, being thrust into the loops (*a a*, Fig. 255).[1]

Fig. 254.—Crumpled Triassic rock, Todi group, Switzerland (real size).

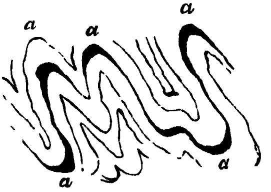

Fig. 255.—Unequal compression of Coal in crumpling, Pembrokeshire (*B.*)

Deformation and Crushing.—During the intense shearing movements to which rocks have been subjected, their individual particles have been compressed, elongated, and made to move past each other, as is instructively shown by the deformation of pebbles and of fossils (p. 314). The most important consequence of this process is the production of the shear-structure already noticed (p. 316). Massive coarsely crystalline pegmatites may be traced through successive stages wherein the component orthoclase and felspar are more and more crushed and drawn out, until in the end the rock becomes a compact finely fissile schist, with a peculiar thready or streaky structure, which can hardly be distinguished from the flow-structure of a rhyolite. This change is more particularly developed along great thrust-planes, but may be observed throughout a mass of rock that has undergone intense shearing.

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[1] For illustrations of this structure see Heim's 'Mechanismus der Gebirgsbildung,' where a terminology for the different parts of folds is proposed.

In many cases lenticular "eyes" of the original rock have been left little or not at all affected, while the portions between them have been crushed and rolled out and have recrystallized more or less completely as true schists (Fig. 332). Sections showing the close connection between mechanical crushing and the production of a schistose structure may be seen abundantly among the Scottish Highlands.[1] In the Silurian district of Guldalen in Norway diabases and other igneous rocks exhibit every stage in the crushing down of eruptive material and its conversion into schists. Similar structures are well displayed among the schists and their accompaniments in Anglesey.

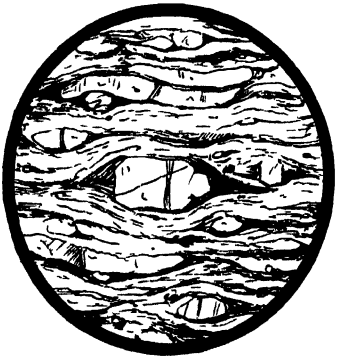

Fig. 256.—Shear-structure Torridon sandstone, Loch Keeshorn. Mag. 30 diam (drawn by Mr. F. W. Rudler). The felspars and other grains have been crushed and flattened, and the matrix made to move past them as in flow-structure (Compare Fig. 80.)

Not only are the individual particles of rocks drawn out by shearing, but in the complicated process of mountain-building, larger features of geological structure likewise undergo deformation. The anticlinal and synclinal folds developed in the earlier stages of the process are sometimes bent over and crushed together, so as to be nearly or completely effaced.

Various experiments have been devised to illustrate the facts of mountain-structure. By a combination of parallel layers of different substances exposed to lateral compression and tension it is possible to imitate many of the features of that structure and to produce very instructive diagrams.[2]

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[1] See *Quart. Journ. Geol. Soc.* xliv. (1888), p. 392.

[2] See for example, A. Favre, *Nature*, xix. p. 103; H. M. Cadell, *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 337. Much information will also be found in Mellard Reade's 'Origin of Mountain Ranges,' 1886.

PART V. CLEAVAGE.

Cleavage-structure having been described at p. 312, we have to notice here the manner in which it presents itself on the large scale among rock-masses. The direction of cleavage usually remains persistent over considerable regions, and, as was shown by Sedgwick,[1] corresponds, on the whole, with the strike of the rocks. It is, however, independent of bedding. Among curved rocks, the cleavage-planes may be seen traversing the plications without sensible deflection from their normal direction, parallelism, and high angle. They must thus be strictly later than these plications. But their general coincidence with the trend of the axes of folding serves to indicate a community of origin for cleavage and folding, as concomitant though not absolutely simultaneous effects of the lateral compression of rocks.[2] Among curved strata, the planes of cleavage sometimes coincide with, and are sometimes at right angles to the planes of bedding, according to the angles of the folding (Fig. 257). The persistence of cleavage-planes across even the most diverse kinds of rock, both sedimentary and igneous, was first described by Sedgwick. Jukes also pointed out that over the whole of the south of Ireland the trend of the cleavage seldom departs 10° from the normal direction E. 25° N., no matter what may be the differences in character and age of the rocks which it crosses. But though cleavage is so persistent, it is not equally well developed in every kind of rock. As already explained (p. 313), it is most perfect in fine-grained argillaceous rocks, which have been altered by it into slates. It is often well developed in felsites and other igneous rocks, which then furnish good flags or even slates. It may be observed at once to change its character as it passes from fine-grained rocks into others of a more granular or gritty texture. Occasional traces of distortion or deviation of the cleavage-planes may be observed at the contact of two dissimilar kinds of rock (Fig. 258).

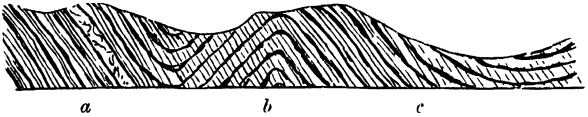

Fig. 257.—Curved and contorted Devonian Rocks, near Ilfracombe (*B.*)
Bedding and cleavage planes are coincident at *a* and *c*, but nearly at right angles at *b*.

A region may have been subjected at successive intervals to the compression that has produced cleavage. The Silurian rocks of the south-west of Ireland were upturned, and probably cleaved, before the deposition of the Old Red Sandstone, which has in turn been well cleaved.[1] Evidence of the relative date of cleavage may be obtained from unconformable junctions and from conglomerates. An uncleaved series of strata, lying upon the denuded edges of an older cleaved series, proves the date of cleavage to be intermediate between the periods of the two groups. Fragments of cleaved rocks in an uncleaved conglomerate show that the rocks whence they were derived had already suffered cleavage, before the detritus forming the conglomerate was removed from them. An intrusive igneous rock, traversed with cleavage-planes like its surrounding mass, points to cleavage subsequent to its intrusion (Fig. 259).[2]

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[1] 'On the Structure of large Mineral Masses,' *Trans. Geol. Soc.* 2nd ser. iii. (1835) —an admirable memoir, in which the structure of a great cleavage region is clearly and graphically described. Phillips gave a good summary of our knowledge up to 1856 in his "Report on Cleavage" in the *British Assoc. Rep.* for that year. But the most exhaustive memoir on the subject is that by Mr. A. Harker in the Reports of the British Association for 1885, p. 813, where copious references to the bibliography will be found. See also papers by the Rev. O. Fisher in *Geol. Mag.* 1884-85, and his 'Physics of the Earth's Crust.'

[2] Harker, *Brit. Assoc. Rep.* 1885, p. 852.

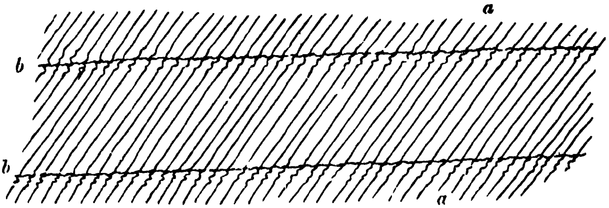

Fig. 258.—Cleaved strata, Wiveliscombe, West Somerset (*B.*)
Showing the cleavage-lines *a a* slightly undulating at the partings of the strata *b b*.

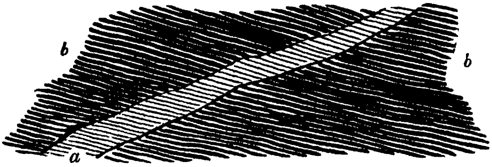

Fig. 259.—Vein of porphyry (*a*) crossing Devonian slates (*b*), Plymouth Sound, both being traversed by cleavage (*B.*)

Between cleavage and foliation there is in many cases a close relation. Microscopic examination of some cleaved rocks shows that in original clastic sediment a micaceous mineral has been abundantly developed, the plates of which are ranged along the planes of cleavage. This mica can be distinguished from original mica-flakes in the sediment. It may be observed, in many cases, to impart a lustrous silvery or silky sheen to the cleavage-faces of a slate, yet may be at right angles to the original lamination of deposit. Such a crystalline rearrangement is indeed an incipient foliation. It is the same structure, further developed and intensified, which gives their distinctive character to schists. The crystalline metamorphosis naturally proceeds along the lines of least resistance, which in cleaved rocks are the cleavage-planes, and in uncleaved sedimentary rocks are the planes of deposition. Foliation, as already remarked (p. 323), may sometimes represent stratification, sometimes cleavage, and sometimes divisional planes superinduced by shearing or faulting.[1]

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[1] De la Beche, 'Geol. Observer,' p. 620.

[2] *Ibid.* p. 621.

Before passing from this subject it may be well to note how deceptive is the resemblance of cleavage-planes to bedding, especially on weathered exposures of rock. Even experienced observers have been misled by this resemblance. At Llanberis, for example, the lower portion of a section consists of volcanic tuff and the upper of conglomerate. The tuff being compact and fine-grained, has undergone such decided cleavage that at first the flags into which it is divided by the cleavage-planes might be mistaken (as they have in fact been) for bedding, and the conglomerate would then be regarded as a much younger deposit lying unconformably on the tuff. In reality, however, the tuff coincides in its bedding with the conglomerate; they are parts of one continuous series, but the coarse-grained conglomerate has been only slightly affected by the pressure which induced the perfect cleavage in the tuff.

PART VI. DISLOCATION.

The movements which the crust of the earth has undergone have not only folded and corrugated the rocks, but have fractured them in all directions. The dislocations may be either simple Fissures, that is, rents without any vertical displacement of the mass on either side, or Faults, that is, rents where one side has been moved relatively to the other.[2] It is not always possible, in a shattered rock, to discriminate between joints and those lines of division to which the term fissures is more usually restricted. Many so-called fissures may be merely enlarged joints. It is common to meet with traces of friction along the walls of fissures, even when no proof of actual vertical displacement can be gleaned. The rock is then often more or less shattered on either side, and the contiguous faces present rubbed and polished surfaces ("slickensides" p. 526). Mineral deposits may also commonly be observed encrusting the cheeks of a fissure, or filling up, together with broken fragments of rock, the space between the two walls. The structure of mineral veins in fissures is described in Part IX.

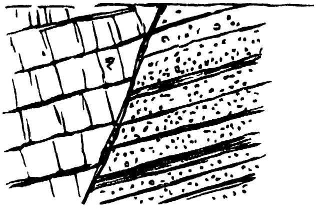

Fig. 260.—Section of sharply-defined Fault without contortion of the rocks.

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[1] See Sedgwick, *Trans. Geol. Soc.* (2), iii. p. 461. Darwin on foliation and cleavage, 'Geological Observations in South America,' 1846, p. 162. A. C. Ramsay, 'Geology of North Wales,' *Mem. Geol. Survey*, vol. iii. 2nd edit. p. 233. F. M. Stapff, *Neues Jahrb.* 1882 (i.), p. 82.

[2] The student of this department of geology will find in the joint essay by M. E. de Margerie and Professor Heim, cited on p. 536, a valuable handbook of the terms used to describe the various structures arising from ruptures of the terrestrial crust.

Nature of Faults.—In a large proportion of cases, however, there has been not only fracture but displacement. The rents have become faults as well as fissures. The movement may have affected only one side of the fissure, or both sides. Sometimes it has consisted in a mere vertical subsidence of one side; in other cases one side has been pushed up, or while one side has moved upward the other has sunk downward, or both sides have been shifted up or down from their original position, but one more than the other. In ordinary faults the displacement is usually vertical or nearly so. But in some regions faults have been produced by a lateral thrust of one side of a fissure past the other side. This structure comes out with remarkable prominence in the gneiss district of western Sutherland, where dykes crossed by such lateral thrusts are disrupted and drawn out along the line of fissure so as to be reduced to a $\frac{1}{45}$ part of their ordinary breadth.[1]

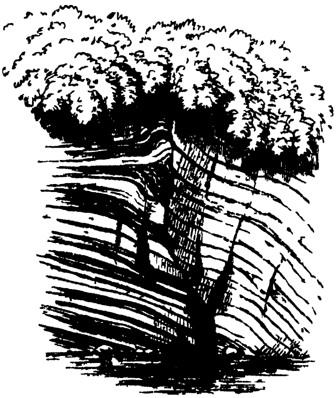

Fig 261.—Section of a Fault, showing disturbance of rocks

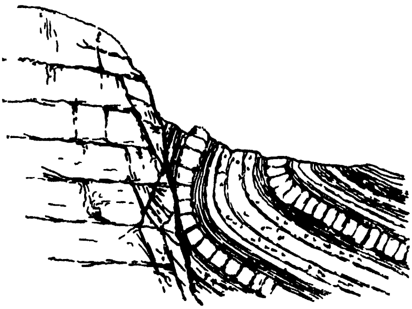

Fig 262 —Section of Fault with inverted beds on the downthrow side

Faults on a small scale are sometimes sharply-defined lines, as if the rocks had been sliced through and fitted together again after being shifted. In such cases, however, the harder portions of the dislocated rocks will usually be found slickensided. More frequently some disturbance has occurred on one or both sides of the fault (Fig. 261). Sometimes in a series of strata, the beds on the side which has been pushed up (or side of upthrow) are bent down against the fault, while those on the opposite side (or that of downthrow) are bent up (Fig. 262). Most commonly the rocks on both sides are considerably broken, jumbled, and crumpled, so that the line of fracture is marked by a belt or wall-like mass of fragmentary rock, known as "fault-rock." Where a dislocation has occurred through materials of very unequal hardness, such as solid limestone bands and soft shales, or where its course has been undulating, the relative shifting of the two sides has occasionally brought opposite prominences together so as to leave wider interspaces (Fig. 312). The actual breadth of a fault may vary from a mere chink into which the point of a knife could hardly be inserted, up to a band of broken and often consolidated materials many yards wide. Where a fault has a considerable throw, it is sometimes flanked by parallel small faults. The occurrence of these close together will obviously produce the appearance of a broad zone of much fractured rock along the trend of a main fissure. A line of disturbance may consist of several parallel faults of nearly equal magnitude (Fig. 265, section 3).

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[1] See Report on Geological Survey work, *Quart. Journ. Geol. Soc.* xliv. (1888), p. 393 and *postea*, Fig. 331.

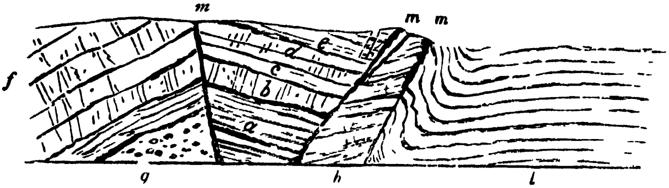

Fig. 263.—Section of group of faults, Coast of Glamorganshire, West of Lavernock Point (*B.*)
m m m, three adjacent faults by which the inclination of the strata is shifted and some of the beds are crumpled; *a*, dolomitic limestone and marl; *b*, *c*, *d*, *e*, *f*, dolomitic limestone; *g*, dolomitic conglomerate; *h*, beds corresponding with those on the left; *l*, Lias, thrown in by a "reversed" fault.

Faults are sometimes vertical, but are generally inclined. The largest faults, or those with the greatest vertical *throw* or displacement, commonly slope at high angles, while those of only a few feet or yards may be inclined as low as 18° or 20°. The inclination of a fault from the vertical is called its *hade*. In Fig. 264, for example, the fault at B, being vertical, has no hade, but that at A hades at an angle of 70° from the vertical to the left hand. The amount of throw is represented as the same in both instances, but with the direction of throw to opposite quarters, so that the level of the beds is raised between the two faults above the uniform horizon which it retains beyond them.

The effect of the inclination of faults is to give the appearance of lateral displacement. In Fig. 264, for example, where the hade of one fault is considerable, the two severed ends (*c* and *d*) of the black bed appear to have been pulled asunder. The horizontal distance to which they are removed does not depend upon the amount of vertical displacement, but upon the angle of hade. A small fault with a great hade will shift strata laterally much more than a large fault with a small hade. It is obvious that the angle of hade must seriously affect the value of a coal-field. If the black bed in the same figure be supposed to be a coal-seam,

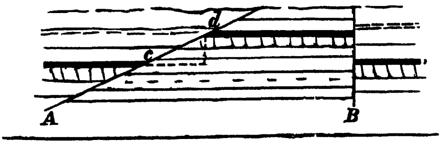

Fig. 264.—Section of inclined and vertical Faults.

it could be worked from either side up to *c* and *d*, but there would be a space of barren ground between these two points, where the seam never could be found. The larger the angle of hade the greater the breadth of such barren ground.

Origin of Faults.—In countries where the rocks have not undergone much disturbance, that is, where stratified formations are still not far removed from their original approximate horizontality, faults are probably, for the most part, due to mere subsidence of the crust (Normal Faults). Where, on the other hand, rocks have been much plicated, the more gigantic faults have been produced by tangential thrust, whereby one mass of rock has been pushed bodily over another (Reversed Faults, Thrust-planes). In some cases, both lateral thrust and subsidence have been concerned in the origin of the dislocations of a much-fractured area.

Normal Faults.—In the vast majority of cases, faults hade in the direction of downthrow, or in other words, they slope away from the side which has risen. These are *Normal Faults.* The explanation of the structure is doubtless to be found in the fact that the portion of the terrestrial crust towards which a fault hades presents a less area of base to pressure or support from below than the mass with the broad base on the opposite side. The mere inspection of a fault in any natural or artificial section suffices, in most cases, to show which is the upthrow side. In mining operations, the knowledge of this rule is invaluable, for it decides whether a coal-seam, dislocated by a fault, is to be sought for by going up or down. In Fig. 264, a miner working from the left, and meeting with the fault at *c*, would know from its hading towards him that he must ascend to find the coal. On the other hand, were he to work from the right, and catch the fault at *d*, he would see that it would be necessary to descend. According to this rule, a normal fault never brings one part of a bed below another part, so as to be capable of being pierced twice by the same vertical shaft.

Reversed Faults are those in which lower rocks on one side have been pushed over higher rocks on the other. In these cases, the same stratum may be pierced twice by a vertical shaft. The hade is therefore in the direction of upthrow. Faults of this kind chiefly occur in regions where the rocks have been excessively plicated, and especially where one-half of a fold has been pushed over another (Figs. 263 and 265, section 4).[1] They are closely connected with anticlinal and synclinal folding. Thus, a monoclinal fold may by increase of movement be developed into a fracture (Fig. 265). Beautiful examples of this relation have been observed by Powell and others among the little-disturbed formations of the great plateaux of Utah and Wyoming. But it is in mountainous regions that they are chiefly developed; they become there, indeed, the common type of dislocation. Many excellent examples have been adduced from the plicated rocks of the Alps.[1]

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[1] If faults were generally due to rupture from compression we should expect the "reversed" to be the ordinary form. The normal hade of faults points to the existence of stresses in the crust of the earth which are from time to time relieved by dislocation. But the nature of these stresses and the manner in which faults arise are still among the obscure problems of geology.

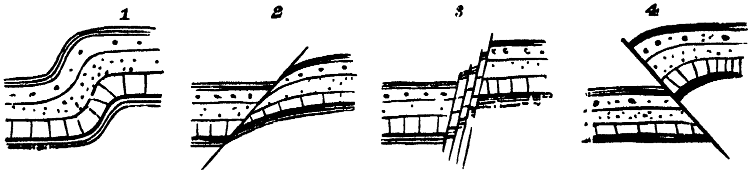

Fig. 265.—Sections to show the relations of Monoclinal folds and faults.
1, Monoclinal fold; 2, Monoclinal fold replaced by a single normal fault; 3, Monoclinal fold converted into a series of parallel normal faults; 4, Monoclinal fold developed by increase of plication into a reversed fault.

Thrust-planes.—Under this name the Geological Survey of Scotland has described a remarkable type of reversed fault, where the hade is so low that the rocks on the upcast side have been pushed for miles horizontally across the rocks on which they lie (see Figs. 249, 311, 328, 331, 334).[2] Such a structure points to enormous tangential pressure, under which the very foundations of a country were thrust up and driven over younger rocks. The "grande faille du Midi," in the north of France and Belgium, by which the Devonian rocks have been pushed over the Carboniferous, is a well-known and remarkable example of this structure. In some cases so intense have been the mechanical movements, that extensive metamorphism has been induced by them. Along the thrust-planes in the north-west of Scotland, and for a long way above them, the rocks that have been pushed forward have undergone enormous shearing, new divisional planes have been developed in them, and they have become more or less schistose, the new minerals crystallizing along the shearing-surfaces approximately parallel to the thrust-planes.

Throw of Faults.—That normal faults are vertical displacements of parts of the earth's crust is most clearly shown when they traverse stratified rocks, for the regular lines of bedding and the originally flat position of these rocks afford a measure of the disturbance. In Fig. 264, the same series of strata occurs, on either side of each of the two faults, so that measurement of the amount of displacement is here obviously simple. The measurement is made from the truncated end of any given stratum vertically to the level of the opposite end of the same stratum on the other side of the fault. Where the fault is vertical, like that to the right in Fig. 264, the mere distance of the fractured ends from each other is the amount of displacement. In the case of an inclined fault, the level of the selected stratum is protracted across the fissure until a vertical from it will reach the level of the same bed, as shown by the dotted lines. The length of this vertical is the amount of vertical displacement, or the *throw* of the fault. The throw of faults varies from less than an inch to several thousand feet.

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[1] See Powell in the works cited already on p. 538. Heim, 'Mechanismus der Gebirgsbildung,' Plate XV. Fig. 14. Compare C. W. Hayes, *Bull. Geol. Soc. Amer.* ii. (1891), p. 141.

[2] B. N. Peach and J. Horne, *Nature*, 13th Nov. 1884. The details of this structure with numerous illustrations will be found in the Report of the Geological Survey, *Quart. Journ. Geol. Soc.* xliv. (1888), p. 378. M. Bertrand has described under the name of "failles courbes" certain curved faults which affect the rocks of the Jura and south of France, but do not, he thinks, descend into the crust; and he cites the Mont Faron near Toulon, which, he says, one cannot climb from any side without crossing a large fault that brings Jurassic down upon Triassic rocks (*Bull. Soc. Géol. France* (3), xii. (1884), p. 452).

Unless beds, the horizons of which are known, can be recognised on both sides of a fault, exposed in a cliff or other section, the fault at that particular place does not reveal the extent of its displacement. It would not, in such a case, be safe to pronounce the fault to be large or small in the amount of its throw, unless we had other evidence from which to infer the geological horizon of the beds on either side. A fault with a considerable amount of displacement may make little show in a cliff, while, on the other hand, one which, to judge from the jumbled and fractured ends of the beds on either side, might be supposed to be a powerful dislocation, may be found to be of comparatively slight importance. Thus, on the cliff near Stonehaven, in Kincardineshire, one of the most notable faults in Great Britain runs out to sea, between the ancient crystalline rocks of the Highlands and the Old Red Sandstones and conglomerates of the Lowlands of Scotland. So powerful have been its effects that the strata on the Lowland side have been thrown on end for a distance of two miles back from the line of fracture, so as to stand upright along the coast-cliffs like books on a library shelf. Yet at the actual point where the fault reaches the sea and is cut in section by the shore-cliff, it is not revealed by a band of shattered rock. On the contrary, no one would at first be likely to suspect the existence of a fault at all. The red sandstone and the reddened Highland schists have been so compressed and, as it were, welded into each other, that some care is required to trace the demarcation between them.

Dip-Faults and Strike-Faults.—The same fault may give rise to very different effects, according to variations in the inclination or curvature of the rocks which it traverses, or to the influence of branch faults diverging from it. Faults among inclined strata may, in most districts, be conveniently grouped into two series, one running in the same general direction as the dip of the strata, the other approximating to the trend of the strike. They are accordingly classified as *dip-faults* and *strike-faults*, which, however, are not always to be sharply marked off from each other, for the dip-faults will often be observed to deviate considerably from the normal direction of dip, and the strike-faults from the prevalent strike, so as to pass into each other.

A dip-fault produces at the surface the effect of a lateral shift of the strata. This effect increases in proportion as the angle of dip lessens, but ceases altogether when the beds are vertical. Fig. 266 may be taken as a plan of a dip-fault (*f f*) traversing a series of strata which dip northwards at 20°. The beds on the east side look as if they had been pushed horizontally southwards. That this apparent horizontal displacement is due really to a vertical movement, and to the subsequent planing down of the surface by denuding agents, will be clear, if we consider what must be the effect of the vertical ascent or descent of the inclined beds at a dislocation. The part on one side of the fracture may be pushed up, or, what is equivalent, that on the other side may be let down. If the strike of the beds be supposed to be east and west, then a horizontal plane cutting the dislocated strata will show the portion on the west or upthrow side of the fault lying to the north of that on the east or downthrow side. The effect of denudation has usually been practically to produce such a plane, and thus to exhibit an apparently lateral shift. This surface displacement has been termed the *heave* of a fault. Its dependence upon the angle of dip of the strata may be seen by a comparison of Sections A and B in Fig. 267. In the former, the bed *a b*, which may be supposed to be one of those in Fig. 266, dipping north at 20°, once prolonged above the present surface (marked by the horizontal line), is represented as having dropped from *w b* to *e d*. The heave amounts to the horizontal distance between *e* and *b*, the throw being the vertical distance between *b* and *d*. But if the angle should rise to 50°, as in B, though the amount of throw or vertical displacement is there one-fourth greater, the heave or horizontal shift diminishes to less than a half of what it is in A. This diminution augments with increase of inclination till among vertical beds there is no heave at all, though a fault with a horizontal thrust will cause a lateral shift even in vertical strata (see Fig. 331).

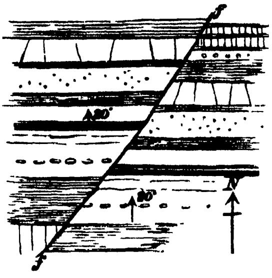

Fig. 266.—Plan of strata cut by a Dip-Fault.

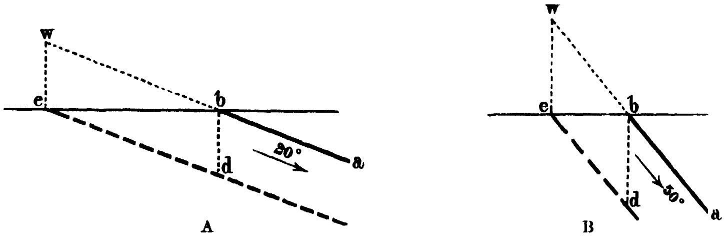

Fig. 267.—Sections to show the variation of horizontal displacement or Heave of Faults, according to the angle of inclination of strata.

Strike-faults, where they exactly coincide with the strike, may remove the outcrops of some strata by never allowing them to reach the surface. Fig. 268 shows a plan (A) and section (B) of one of these faults, *f f*, having a downthrow towards the direction of dip. In crossing the strike, we pass successively over the edges of all the beds, except the part between the asterisks, which is cut out by the fault as shown in the section. It seldom happens, however, that such strict coincidence between faults and strike continues for more than a short distance. The direction of dip is apt to vary a little even among comparatively undisturbed strata, every such variation causing the strike to undulate, and thus to be cut more or less obliquely by the line of dislocation, which may nevertheless run quite straight. Moreover, an increase or diminution in the throw of a strike-fault will have the effect of bringing the dislocated ends of the beds against the line of dislocation. In Fig. 269, for instance, which represents in plan another strike-fault (*f*), we see that the amount of throw increases towards the right so as to allow lower beds successively to appear on one side, while towards the left it diminishes, and finally dies out in bed Y.

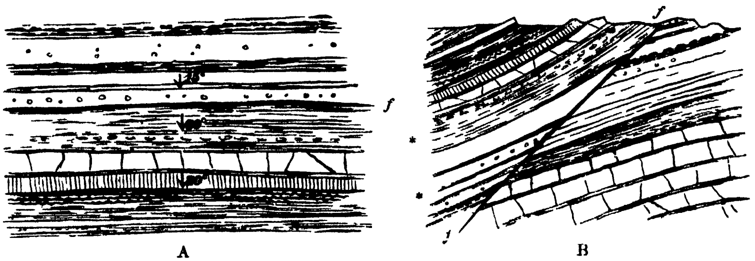

Fig 268.—Strike-Fault.
A, Plan, B, Section across the plan in the line of the arrows.

Their effects become more complicated where faults traverse undulating and contorted strata. The connection between folding and fracture has already been adverted to in the case of monoclinal bends. It sometimes happens that the plications are subsequently fractured, so that the fault may appear to be alternately a downthrow on opposite sides, according to the position of the arches and troughs which it crosses. This structure may be illustrated by a plan and sections of a dislocated anticline and syncline, which will also show clearly how the apparently lateral displacement of outcrop produced by dip-faults is due to vertical movement. Fig. 270 represents a plan of strata thrown into an anticlinal fold AA and a synclinal fold SS, and traversed by a fault FF, having an upthrow (*u u*) to the east. A dip-fault shifts the outcrop towards the dip on the upthrow side, and this will be observed to be the case here. On the west side of the fault, the black bed *a*, dipping towards the south, is truncated by the fault at *u*, and the portion on the upthrow side is shifted forwards or southward. Crossing the syncline we meet with the same bed rising with a contrary dip, and as the upthrow of the fault still continues on the same side, the portion of the bed on the west side of the fault must be sought further south. The effect of the

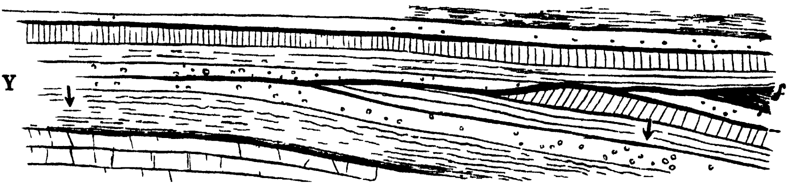

Fig 269.—Plan of strata traversed by a diminishing Strike Fault

fault on the syncline is to widen the distance between the two opposite outcrops of a bed on the downthrow side, or to narrow it on the upthrow side. On the southern slope of the anticline A, the same bed once more appears, and again is shifted forwards, as before, on the upthrow side. Hence in an anticline, the reverse effect takes place, for there the space between the two outcrops is narrowed on the downthrow side. A section along the east or upcast side of the fault would give the structure represented in Fig. 271 (1); while one along the downcast side would be as in (2). These two sections illustrate how the shifting of the outcrops at the surface can be simply explained by a mere vertical movement.

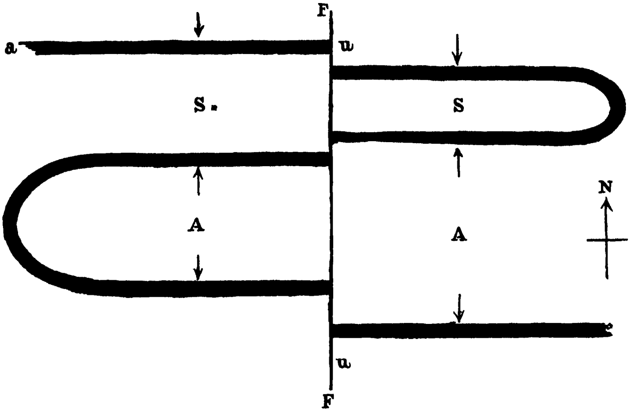

Fig. 270.—Plan of Anticline (A) and Syncline (S), dislocated by a Fault (F F).

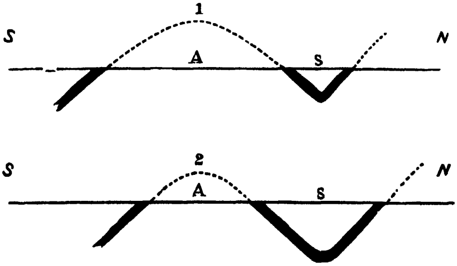

Fig. 271.—Sections along the Fault in Fig. 270.
1 Section along the upcast side; 2, Section along the downthrow side.

Dying out of Faults.—Dislocation may take place either by a single fault, or as the combined effects of two or more. Where there is only one fault, one of its sides may be pushed up or let down, or there may be a simultaneous opposite movement on either side. In such cases, there must be a gradual dying out of the dislocation towards either end; and one or more points where the displacement has reached a maximum. Sometimes, as may be seen in coal-workings, a fault, with a considerable maximum throw, splits into minor faults at the terminations. In other cases, the offshoots take place along the line of the main fissure. Exceedingly complicated examples occur in some coal-fields, where the connected faults become so numerous that no one of them deserves to be called the main or leading dislocation. By a series of branch-faults, the effect of a main fault may be neutralised or reversed. Suppose, for example, that a main fault at its eastern portion throws down 60 fathoms to the north, and that at intervals three faults on the same side strike off from it, each having a downthrow of 25 fathoms to the east; the combined effect of these branch faults will be to reverse the throw of the main fault towards its western end, and produce a downthrow of 15 fathoms to the south.

Groups of Faults.—The subsidence or elevation of a large mass or block of rock has usually taken place by a combination of faults. Detailed maps of coal-fields, such as those published by the Geological Survey of Great Britain on a scale of six inches to a mile, furnish much instructive material for the study of the way in which the crust of the earth has been reticulated by faults. In most cases, dip-faults are predominant, sometimes to a remarkable extent, as in the portion of the South Wales coal-field represented in Fig. 272. In other places, the dislocations run in all directions, so as to divide the ground into an irregular network.

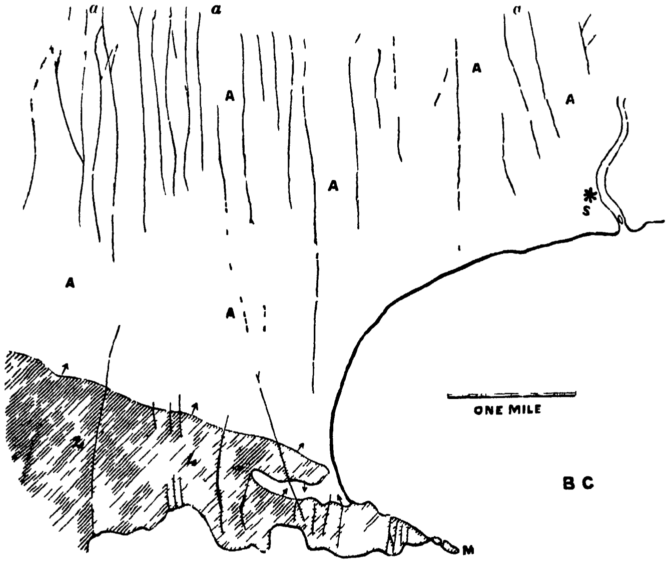

Fig 272.—Map of part of the South Wales Coal-field.
A A, Coal measures L L, Carboniferous limestone dipping beneath the coal-measures as shown by the arrows, a a, dip faults, S, Swansea, M, the Mumbles, B C, Bristol Channel

It often happens that, by a succession of parallel and adjoining faults, a series of strata is so dislocated that a given stratum, which may be near the surface on one side, is carried down by a series of steps to some distance below. Excellent examples of these step-faults (Fig. 273) are to be seen in the coal-fields on both sides of the upper part of the estuary of the Forth. Instead, however, of having the same downthrow, parallel faults frequently show a movement in opposite directions. If the mass of rock between them has subsided relatively to the surrounding ground, they are trough-faults (Fig. 274), and enclose wedge-shaped masses of rock. It will be observed that the hade of these faults is in each case towards the downthrow side, and that the wedge-shaped masses with broad bottoms have risen, while those with narrow bottoms and broad tops have sunk.

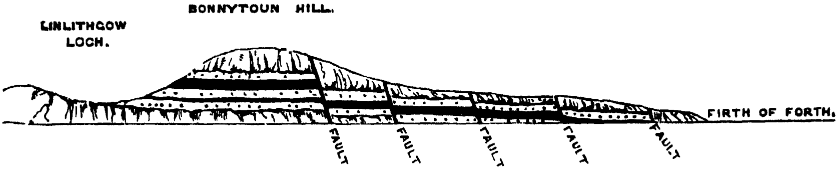

Fig. 273.—Step-Faults, Linlithgowshire.

The faults of a district may not have been the result of one series of movements, but of a long succession of displacements, or of renewed disturbance after prolonged quiescence. One fault sometimes displaces another. In regions of reversed faults and thrust-planes, normal faults have sometimes taken place long after the first dislocations. In north-western Scotland, for example, the thrust-planes have been cut across and shifted, exactly as if they had been ordinary stratification-planes.

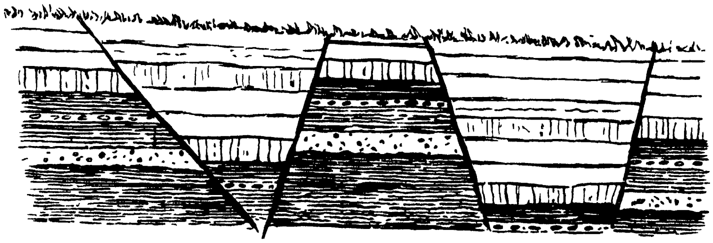

Fig 274.—Trough-Faults.

Detection and tracing of Faults.—As a rule, faults give rise to little or no feature at the surface, so that their existence would commonly not be suspected. They comparatively rarely appear in visible sections, but are apt rather to conceal themselves under surface accumulations just at those points in a ravine or other natural section where we might hope to catch them. Yet they undoubtedly constitute one of the most important features in the geological structure of a district or country, and should consequently be traced with the greatest care. In the majority of cases, in countries like much of central and northern Europe, where the ground is covered with superficial deposits, the position of faults cannot be seen, but must be inferred; though it must be admitted that geologists have been prone to great recklessness in this respect, introducing faults for which there was little or no actual evidence, but which were convenient for the explanation of theoretical views of the structure of a district. Experience will teach the student that the mere visible section of a fault on some cliff or shore does not necessarily afford such clear evidence of its nature and effects as may be obtained from other parts of the region, where it does not show itself at the surface at all. In fact, he might be deceived by a single section with a fault exposed in it, and might be led to regard that fault as an important and dominant one, while it might be only a secondary dislocation in the near neighbourhood of a great fracture, for which the evidence would be elsewhere obtainable, but which might never be seen itself. The actual position (within a few yards) of a large fault, its line across the country, its effect on the surface, its influence on geological structure, its amount of vertical displacement at different parts of its course—all this information may be admirably worked out, and yet the actual fracture may never be seen in any one single section on the ground. A visible exposure of the fracture would be interesting: it would give the exact position of the line at that particular place; but it would not be necessary to prove the existence of the fault, nor would it perhaps furnish any additional information of importance. The existence of an unseen fault may usually be determined by an examination of the geological structure of a district. An abruptly truncated outcrop is always suggestive of fracture, though sometimes it may be due to unconformable deposition against a steep declivity. If a series of strata be discovered, in a water-course or other exposure, dipping continuously in one general direction at angles of 10° or more, and if, at a short distance, another portion of the same series be found inclined in another direction, the two thus striking at each other, a fault will almost always be required to

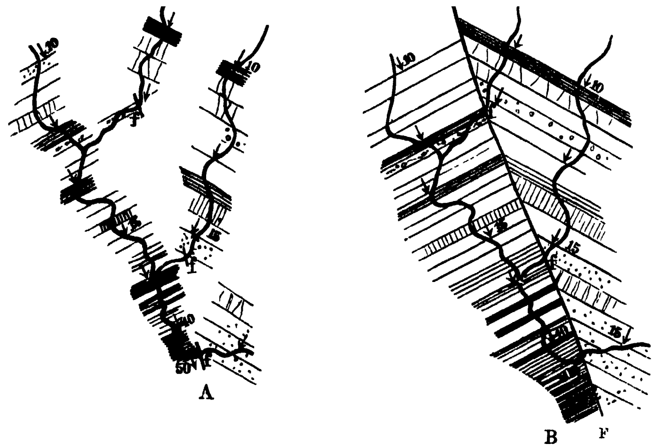

Fig. 275.—Map, illustrating the detection of an unseen Fault.
A, Field-map, showing the data actually obtained on the ground; B, completed Map, showing the geological structure of the district.

explain their relation. If all the evidence obtainable, from the sections in water-courses or otherwise, be put upon a map (as in A, Fig. 275), it will be seen that a dislocation must run somewhere near the points marked *f f*, as there is no room for either series to turn round so as to dip below the other. They must be mutually truncated. The completed map would represent them separated by a fault (F, in B). The upthrow or downcast side of the dislocation would be determined by the observer's knowledge of the order of superposition of the respective groups of strata.

The existence of a fault having been thus proved from an examination of the geological structure of the ground, its line across the country may be approximately laid down—1st, by getting exposures of the two sets of rock, or the two ends of a severed outcrop on either side, as near as possible to each other, and tracing the trend of the dislocation between; 2nd, by noting lines of springs along the supposed course of the fault, subterranean water frequently finding its way to the surface along such fissures; 3rd, by attending to surface features, such as lines of hollow, or of ridge rising above hollow, the effect of a fault often being to bring rocks of unequal resistance together, so as to allow the more durable to rise more or less steeply from the fracture.[1]

PART VII. ERUPTIVE (IGNEOUS) ROCKS AS PART OF THE STRUCTURE OF THE EARTH'S CRUST.

The lithological differences of eruptive rocks having already been described in Book II. (p. 154), it is their larger features in the field that now require attention,—features which, in some cases, are readily explicable by the action of modern volcanoes; and which, in other cases, bring before us parts of the economy of volcanoes never observable in any recent cone, by revealing deep-seated rock-structures that lie far beneath the upper or volcanic zone of the terrestrial crust. A study of the igneous rocks of former ages, as built up into the framework of the crust, serves to augment our knowledge of volcanic action.

At the outset, it is evident that if eruptive rocks have been extruded from below in all geological ages, and if, at the same time, denudation of the land has been continuously in progress, many masses of molten material, poured out at the surface, must have been removed. But the removal of these superficial sheets would uncover their roots or downward prolongations, and the greater the denudation, the deeper down must have been the original position of the rocks now exposed to daylight. Fig. 276, for example, shows a district in which a series of tuffs and breccias

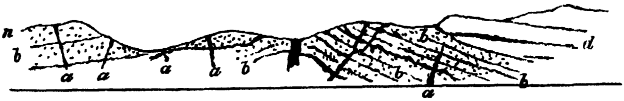

Fig. 276.—Extensively-denuded Volcanic District (*B.*)

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[1] See 'Field Geology,' by the author, chapter x.

(*bb*) traversed by dykes (*aa*) is covered unconformably by a newer series of deposits (*d*). Properly to appreciate the relations and history of the rocks, we must bear in mind that originally they may have presented some such outline as in Fig. 277, where the present surface (that of Fig. 276) down to which denudation has proceeded is represented by the dotted line *n s.*[1] We may therefore *a priori* expect to encounter different levels of eruptivity, some rocks being portions of sheets that solidified at the surface, others forming parts of injected sheets or of the pipe or column that connected the superficial sheets with the internal lava-reservoir. We may infer that many masses of molten rock, after being driven so far upward, came to rest without ever finding their way to the surface. It cannot always be affirmed that a given mass of intrusive igneous rock, now denuded and exposed at the surface, was ever connected with any superficial manifestation of volcanic action.

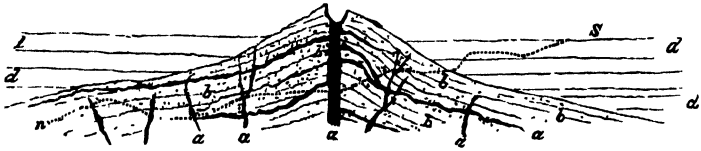

Fig. 277.—Restored outline of the original form of ground in Fig. 276 (*B.*)

Now there will obviously be, as a general rule, some difference in texture, if not in composition, between the superficial and the deep-seated masses, and this difference is of so much importance in the interpretation of the history of volcanic action that it ought to be clearly kept in view. Those portions of an eruptive mass which consolidated at some depth are generally more coarsely crystalline than those which flowed out as lava; they are likewise destitute of the cellular scoriaceous structure and the ashy accompaniments so characteristic of superficial igneous rocks. Yet even if there were no well-marked petrographical contrast between the two groups, it would manifestly lead to confusion if no distinction were drawn between those igneous masses which reached the surface and consolidated there, like modern lava-streams or showers of ashes, and those which never found their way to the surface, but consolidated at a greater or less depth beneath it. There must be the same division to be drawn in the case of every active volcano of the present day. But at a modern volcano, only the materials which reach the surface can be examined, the nature and arrangement of what still lies underneath being matter of inference. In the revolutions to which the crust of the earth has been subjected, however, denudation has, on the one hand, removed superficial sheets of lava and tuff, and has exposed the subterranean continuations of the erupted rocks, and, on the other hand, has laid open the very heart of masses which, though eruptive, seem never to have been directly connected with actual volcanic outbursts. All subterranean intruded masses, now revealed at the surface after the removal of some depth of overlying rock, may be grouped together into one division under the names Plutonic, Intrusive, or Subsequent. On the other hand, all those which came up to the surface as ordinary volcanic rocks, whether molten or fragmental, and were consequently contemporaneously interstratified with the formations which happened to be in progress on the surface at the time, may be classed in a second group under the names Volcanic, Interbedded, or Contemporaneous.

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[1] De la Beche, 'Geol. Observer,' p. 561.

It is obvious that these can be used only as relative terms. Every truly volcanic mass which, by being poured out as a lava-stream at the surface, came to be regularly interstratified with contemporaneous accumulations, must have been directly connected below with molten matter which did not reach the surface. One part of the total mass, therefore, would be included in the second group, while another portion, if ever exposed by geological revolutions, would be classed with the first group. Seldom, however, can the same masses which flowed out at the surface be traced directly to their original underground prolongations.

It is evident that an intrusive mass, though necessarily subsequent in age to the rocks through which it has been thrust, need not be long subsequent. Its relative date can only be certainly affirmed with reference to the rocks through which it has broken. It must obviously be younger than these, even though they lie upon it, if they bear evidence of alteration by its influence. The probable geological date of its eruption must be decided by evidence to be obtained from the grouping of the rocks all around. Its intrusive character can only certainly determine the limit of its antiquity. We know that it must be younger than the rocks it has invaded; how much younger, must be otherwise determined. Thus, a mass of granite or a series of granite veins (*a a*, Fig. 278) is manifestly posterior in date to the plicated rocks (*b b*) through which it has risen. But it must be regarded as older than overlying undisturbed and unaltered rocks (*c*), or than others lying at some distance (*e f*), which contain worn fragments derived from the granite.

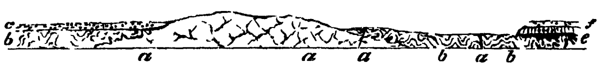

Fig 278.—Section showing the relative age of an Intrusive Rock (B.)

On the other hand, an interbedded or contemporaneous igneous rock has its date precisely fixed by the geological horizon on which it lies. Sheets of lava or tuff interposed between strata in which such fossils as *Calymene Blumenbachii*, *Leptæna sericea*, *Atrypa reticularis*, *Orthis elegantula*, and *Pentamerus Knightii* occur, would be unhesitatingly assigned by a geologist to submarine volcanic eruptions of Upper Silurian age. A lava-bed or tuff intercalated among strata containing *Sphenopteris affinis*, *Lepidodendron veltheimianum*, *Leperditia*, and other associated fossils, would unequivocally prove the existence of volcanic action at the surface during the Lower Carboniferous period, and at that particular part of the period represented by the horizon of the volcanic bed. Similar eruptive material associated with *Ammonites*, *Belemnites*, *Pentacrinites*, &c., would certainly belong to some zone in the great Mesozoic suite of formations. An interbedded and an intrusive mass found on the same platform of strata need not necessarily be coeval. On the contrary, the latter, if clearly intruded along the horizon of the former, would obviously be posterior in date. It will be understood, then, that the two groups have their respective limits determined mainly by their relations to the rocks among which they may happen to lie, though there are also special internal characters that help to discriminate them.

The value of this classification for geological purposes is great. It enables the geologist to place and consider by themselves the granites, quartz-porphyries, and other crystalline masses, which, though lying sometimes perhaps at the roots of ancient volcanoes, and therefore intimately connected with volcanic action, yet owe their special characters to their having consolidated under pressure at some depth within the earth's crust; and to arrange in another series the lavas and tuffs which, having been thrown out to the surface, bear the closest resemblance to the ejected materials from modern volcanoes. He is thus presented with the records of hypogene igneous action in the one group, and with those of superficial volcanic action in the other. He is furnished with a method of chronologically arranging the volcanic phenomena of past ages, and is thereby enabled to collect materials for a history of volcanic action over the globe.

In adopting this classification for unravelling the geological structure of a region where igneous rocks abound, the student will encounter instances where it may be difficult or impossible to decide in which group a particular mass of rock must be placed. He will bear in mind, however, that, after all, such schemes of classification are proposed only for convenience in systematic work, and that there are no corresponding hard and fast lines in nature. He will recognise that all crystalline or glassy igneous rocks must be intrusive at a greater or less depth from the surface; for every contemporaneous sheet has obviously proceeded from some internal pipe or mass, so that, though interbedded and contemporaneous with the strata at the top, it is intrusive in relation to the strata below.

The characters by which an eruptive (igneous) rock may be distinguished are partly lithological and partly geotectonic. The lithological characters have already been fully given (pp. 135, 154). Among the more important of them are the predominance of silicates (notably of felspars, hornblende, mica, augite, olivine, &c.), and of disseminated crystals of iron oxides (magnetite, titaniferous iron); a prevailing more or less thoroughly crystalline structure; the frequent presence of vitreous and devitrified matter, visible megascopically or microscopically; and the occurrence of porphyritic, cellular, pumiceous, slaggy, amygdaloidal, and fluxion structures. These characters are never all united in the same rock. They possess likewise various values as marks of eruptivity, some of them being shared with crystalline schists which were certainly not eruptive. On the whole, the most trustworthy lithological evidence of the eruptive character of a rock is the presence of glass, or traces of an original glassy base. We do not yet certainly know of any natural vitreous substance, except of an eruptive nature. The occurrence or association of certain minerals, or varieties of minerals, in a rock, may also afford presumptive evidence of its igneous origin. Sanidine, leucite, olivine, nepheline, for example, are, for the most part, characteristic volcanic minerals; and mixtures of finely crystallized triclinic felspars with dark augite, olivine, and magnetic iron, or with hornblende, are specially met with among eruptive rocks.

But it is the geotectonic characters on which the geologist must chiefly rely in establishing the eruptive nature of rocks. These vary according to the conditions under which the rocks have consolidated. We shall consider them as they are displayed by the Plutonic, or deep-seated, and Volcanic, or superficial phase of eruptivity.[1]

Section i. Plutonic, Intrusive, or Subsequent Phase of Eruptivity.

We have here to consider the structure of those eruptive masses which have been injected or intruded into other rocks, and have consolidated beneath the surface. One series of these masses is crystalline in structure, but with felsitic and vitreous varieties. It includes most of the eruptive rocks, and especially the more coarsely crystalline forms (granite, syenite, quartz-porphyry, granophyre, liparite, diorite, &c.) The other series is fragmental in character, and includes the agglomerates and tuffs which have filled up volcanic orifices.

After some practice, the field-geologist acquires a faculty of discriminating, even in hand-specimens, crystalline rocks which have consolidated beneath the surface, from those which have flowed out as lava-streams. Coarsely crystalline granites and syenites, with no trace of any vitreous ground-mass, are readily distinguishable as plutonic masses; while, on the other hand, cellular or slaggy lavas are easily recognisable as superficial outflows, or as closely connected with them. But it will be observed that such differences of texture, though furnishing useful helps, are not to be regarded as always and in all degrees perfectly reliable. We find, for example, that some lavas have appeared at or near the surface with so coarsely crystalline a structure as to be mistaken by a casual observer for granite; while, on the other hand, though an open pumiceous or slaggy structure is certainly indicative of a lava that has consolidated at or near the surface, a finely cellular character is not wholly unknown in intrusive sheets and dykes which have consolidated below ground. Again, masses of fragmentary volcanic material are justly regarded as proofs of the superficial manifestation of volcanism, and in the vast majority of cases, they occur in beds which were accumulated on the surface, as the result of successive explosions. Yet cases, which will be immediately described, may be found in many old volcanic districts, where such fragmentary materials, falling back into the volcanic funnels, and filling them up, have been compacted there into solid rock; they may occasionally have been produced by explosions of lava within subterranean caverns.

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[1] As already stated (p. 125), a chronological basis has been proposed for the classification of eruptive rocks. Some writers have even gone so far as to suggest that different names should be given to eruptive rocks according to the geological formation in which they occur, as *Carbophyre*, *Kohlephyre*, *Triaphyre*, *Juraphyre*. See Th. Ebray, *Bull. Soc. Géol. France* (3), iii. p. 291.

The general law which has governed the intrusion of igneous rock within the earth's crust may be thus stated: Every fluid mass impelled upwards by pressure from below, or by the expansion of its own imprisoned vapour, has sought egress along the line of least resistance. That line has depended in each case upon the structure of the terrestrial crust and the energy of eruption. It may have been determined by an already existent dislocation, by planes of stratification, by the surface of junction of two unconformable formations, by contemporaneously formed cracks, or by other more complex lines of weakness. Sometimes the intruded mass has actually fused and obliterated some of the rock which it has invaded, incorporating a portion into its own substance. The shape of the channel of escape has thus determined the external form of the intrusive mass, as the mould regulates the form assumed by cast-iron. This relation offers a very convenient means of classifying intrusive rocks. According to the shape of the mould in which they have solidified, they may be arranged as—(1) bosses or amorphous masses, (2) sheets, (3) veins and dykes, and (4) necks.

§ 1. Bosses.

Bosses or amorphous masses consist chiefly of crystalline, coarse-textured rocks. Granite and syenite are the most conspicuous examples, but various quartz-porphyries, felsites, trachytes, diorites, gabbros, diabases, andesites, dolerites, etc., also occur. Where rocks assume this form as well as that of sheets, dykes, and contemporaneous beds, it is commonly observed that they are more coarsely crystalline when in large amorphous masses than in any other form. Pyroxenic rocks afford many examples of this characteristic. In the basin of the Forth, for instance, while the outflows at the surface have been fine-grained basalts, the masses consolidated underneath have generally been coarse dolerites or diabases.[1]

In the consolidation of an igneous rock, the more basic minerals have generally crystallized out first, and the last portions of the mass to solidify have not infrequently a notably more acid character than those which solidified first. Hence the margin of an eruptive mass may show a more basic composition than the central portions which cooled more slowly. A remarkable range of composition may thus be found within the same boss.[2] Again, if during the process of consolidation a rock should be ruptured and portions of the still liquid matter be forced into the rents, these veins or squirts will generally be found to be decidedly more acid than the rock in which they lie (pp. 225, 262, 269).

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[1] *Trans. Roy. Soc. Edin.* xxix. p. 493 (1879).

[2] Teall and Dakyns, *Quart. Journ. Geol. Soc.* 1892, p. 104.

Granite.—It was once a firmly-held tenet that granite is the oldest of rocks, the foundation on which all other rocks have been laid down. This idea no doubt originated in the fact that granite is found rising from beneath gneiss, schist, and other crystalline masses, which in their turn underlie very old stratified formations. The intrusive character of granite, shown by its numerous ramifying veins, proved it to be later than at least those rocks which it had invaded. Nevertheless, the composition and structure of gneiss and mica-schist were believed to be best explained by supposing these rocks to have been derived from the waste of granite, and thus, though the existing intrusive granite had to be recognised as posterior in date, it was regarded as only a subsequent protrusion of the vast underlying granitic crust. In this way, the idea of the primeval or fundamental nature of granite held its ground. From what is known regarding the fusion and consolidation of rocks (*ante*, p. 300 *et seq.*), and from the evidence supplied by the microscopic structure of granite itself (p. 112), it appears now to be established that granite has consolidated under great pressure, in presence of superheated water, with or without liquid carbon-dioxide, fluorine, &c., conditions which probably never obtained at the earth's immediate surface, unless, perhaps, in those earliest ages when the atmosphere was densely loaded with vapours, and when the atmospheric pressure at the surface must have been enormous (p. 35). Whether the original crust was of a granitic or of a glassy character, no trace of it has ever been or is ever likely to be found. There can be no doubt, however, that the oldest known rocks are either granites or granitoid gneisses which have probably been formed out of granite.

The presence of granite at the existing surface is, doubtless, in all cases due to the removal by denudation of masses of rock under which it originally consolidated. The fact that, wherever extensive denudation of an ancient series of crystalline rocks has taken place, a subjacent granitic nucleus is apt to appear, does not prove granite to be of primeval origin. It shows, however, that the lower portions of crystalline rocks very generally assume a granitic type, and it suggests that if, at any part of the earth, we could bore deep enough into the crust, we should probably come to a granitic layer. That this layer, even if general round the globe, is not everywhere of the highest geological antiquity, or at least has consolidated at widely different periods, is abundantly clear from the fact that in many cases it can be proved to be of later date than fossiliferous formations the geological position of which is known; that is, the granitic layer has invaded these formations, rising up through them, and possibly melting down portions of them in its progress. Granite invades and alters rocks of all ages up to late Mesozoic and Tertiary formations. Hence, it does not belong exclusively to the earliest nor to any one geological period, but has rather been extruded at various epochs, and may even be in course of extravasation now, wherever the conditions required for its production still exist. As a matter of fact, granite occurs much more frequently in association with older, and therefore lower, than with newer and higher rocks. But a little reflection shows that this ought to be the case. Granite, having a deep-seated origin, must rise through the lower and more ancient masses before it can reach the overlying more recent formations. But many protrusions of granite would, doubtless, never ascend beyond the lower rocks. Subsequent denudation would be needed to reveal these protrusions, and this very process would remove the later formations, and, at the same time, any portions of the granite which might have reached them.

Granite frequently occurs in the central parts of mountain chains; sometimes it forms there a kind of core to the various gneisses, schists, and other crystalline rocks. It appears in large eruptive bosses, which traverse indifferently the rocks on the line of which they rise, and commonly send out abundant veins into them. Sometimes it even overlies schistose and other rocks, as in the Piz de Graves in the upper Engadine, where a wall-like mass of granite, with syenite, diorite, and altered rocks, may be seen resting upon schists.[1] In the Alps and other mountain ranges, it is found likewise in large bed-like masses which run in the same general direction as the rocks with which they are associated.

Reference has already been made (p. 157) to some of the more marked varieties of texture and structure in granite bosses. To a few of these further and more detailed remarks may be appropriately inserted here. The patches or enclosures in granite, which differ in colour, texture, and composition from the general mass of the rock, may be grouped in two divisions; 1st. Angular or subangular fragments, probably in most cases derived from the rocks through which the granite has been protruded. These are sometimes tolerably abundant towards the outer margin of a boss. They usually show considerable contact-metamorphism, due no doubt to the influence of the eruptive rock in which they are enclosed. 2nd. Globular or rounded concretions, due to some process of segregation and crystallization, in the original still unconsolidated granite. Examples of this nature occur in the Cornish and Devon granite, as in Fig. 279, which was long ago cited by De la Beche as showing a central cavity (*a*), not quite filled with long crystals of schorl surrounded with an envelope of quartz and schorl (*b*), outside of which lies a second envelope (*c*) of the same minerals, the schorl predominating, the whole being contained in a light flesh-coloured and markedly felspathic granite (*d*). But more remarkable concretionary forms have since been observed in many granites, some of them presenting an internal radial concentric arrangement, and recalling the orbicular structure of some diorites (Napoleonite) (Fig. 8). Such concretionary aggregations are generally more basic than the surrounding granite.[2]

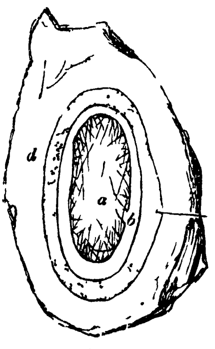

Fig 279 —Crystalline geode in granite, Dartmoor (*B*)

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[1] **Studer**, 'Geologie der Schweiz,' i. p. 290.

[2] **Besides** the papers of Phillips, Brogger, and Hatch cited on p. 159, see on enclosures in

Of more importance, as affecting a much larger proportion of a granite boss, are the differences of texture and of structure not infrequently traceable from the margin to the centre. Like most intrusive rocks, granite is apt to be more close-grained at its contact with the surrounding strata than in the centre of its mass, though it does not show this contrast so strikingly as the more basic rocks such as gabbro, diabase, and dolerite. Certain characteristic varieties of texture and even to some extent of composition may, however, be recognised in many granite areas. In particular the marginal portions not infrequently present a remarkable foliated arrangement which simulates the structure of gneiss, the folia being rudely parallel to the margin of contact and either vertical or dipping at high angles away from the core of granite. In some granite bosses a striking gradation can be traced even into picrites and serpentines.

A detailed study has been made by Dr. Charles Barrois of the granulites (*i.e.* granites with two micas) of the Morbihan in Brittany. He has shown that the large bosses measuring some hundreds of square kilometres present certain well-marked modifications not only of structure but of composition as they are traced from the centre to the periphery, while the smaller bosses show no such modifications and are to be regarded merely as apophyses from those of large size. The modifications along the contact do not arise from any exchange of substance between the granite and the surrounding rock, but solely from the influence of cooling which has affected the orientation of the minerals, their grouping and their order of crystallization. Where the granite has risen parallel to the strike of the adjacent strata it usually passes from its ordinary granular into a porphyroid structure, with its large constituents arranged parallel as in flow-structure; where on the other hand it breaks across the bedding it has assumed a finely granular massive character (aplite) with its crystalline constituents showing regular geometric forms. These variations are thus proved in this particular instance to depend on the influence of the surrounding envelope, which though chemically inactive, offers considerable diversity as a conductor of heat and of pressure. The crystallization of the constituents of the rock took place progressively from the outside inwards, that is, from a mass still in motion across a magma that had come to rest and which shows now no trace of flow. But besides this marginal band of "porphyroid granulite," the external portions of the southern flanks of the bosses present a remarkable schistose structure which, likewise limited to a peripheral zone, resembles that of gneiss, both fine-grained and glandular (angen-gneiss). Examined in detail the mica-flakes of this gneissic band are found to be torn and drawn out, the felspar crystals deformed, broken, and blunted, indicating the powerful mechanical forces which have affected the rock. These crushed constituents have subsequently been re-cemented by membranes and fibres of white sericitic mica, sometimes of black mica, and by sheets of secondary granular quartz, formed out of the triturated débris of the older ingredients. Considering the gradual passage of these schistose selvages into the ordinary granular rock, and the further fact that the schistose structure occurs only on the southern flanks of the granitic bosses of the Morbihan, Dr. Barrois attributes this structure to a powerful lateral pressure which has acted in a direction from south to north.[1]

Relation of Granite to contiguous Rocks.—From an early period the attention of geologists has been given to the evident mineralogical change which has taken place among stratified rocks as

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the Shap granite Harker and Marr, *Quart. Journ. Geol. Soc.* xlvii. (1891), p. 280; on gradation of granite into basic rocks, Teall and Dakyns, cited on p. 564.

[1] *Ann. Soc. Géol. Nord,* xv. 1887, pp. 1-40.

they approach a mass of granite. This change is developed within a ring or areola which encircles the granite, and varies in breadth from a few yards to two or three miles. The most intense alteration is found next the granite, while along the outer margin of the areola the normal character of the rocks is resumed. In some cases, however, no perceptible trace of alteration can be detected next a mass of granite. Of the European examples of contact-metamorphism, those of Devon and Cornwall, Ireland, Scotland, the Harz, Vosges, Pyrenees, and Norway have long been known. The nature of the metamorphism thus superinduced upon rocks is more particularly discussed at p. 605.

The south-east of Ireland supplies an admirable illustration of the relation between granite and its surrounding rocks (Fig. 280). A mass of granite 70 miles in length and from 7 to 17 in width there stretches from north-east to south-west, nearly along the strike of the Lower Silurian rocks. These strata, however, have not been upraised by it in such a way as to expose their lowest beds dipping away from the granite. On the contrary, they seem to have been contorted prior to the appearance of that rock; at least they often dip towards it, or lie horizontally or undulate upon it, apparently without any reference to movements which it could have produced. As Jukes showed, the Silurian strata are underlain by a vast mass of Cambrian rocks, all of which must have been invaded by the granite before it could have reached its present horizon. He infers that the granite must have slowly and irregularly eaten its way upward through the Silurian rocks, absorbing much of them into its own mass as it rose. For a mile or more, the stratified beds next the granite have been altered into mica-schist, and are pierced by numerous veins from the invading rock. Within the margin of the granitic mass, belts or rounded irregular patches of schist (*b b*) are enclosed; but in the central tracts, where the granite is widest, and where therefore we may suppose the deepest parts of the mass have been laid bare, no such included patches of altered rock occur. From the manner in which the schistose belt is disposed round the granite, it is evident that the upper surface of the latter rock, where it extends beneath the schists, must be very uneven. Doubtless the granite rises in some places much nearer to the present surface of the ground than at others, and sends out veins and strings which do not appear above ground. If, as Jukes supposed, a thousand feet of the schists could be restored at some parts of the granite belt, no doubt the belt would there be entirely buried; or if, on the other hand, the same thickness of rock could be stripped off some parts of the band of schist, the solid granite underneath would be laid bare. The extent of granite surface exposed must thus be largely determined by the amount of denudation, and by the angle at which the upper surface of the granite is inclined beneath the schists. Where the inclination is high, prolonged denudation will evidently do comparatively little in widening the belt.[1] But where the slope is gentle, and especially where the surface undulates, the removal, for some distance, of a comparatively slight thickness of rock, may uncover a large breadth of underlying granite. Portions of the metamorphosed rocks left by denudation upon the surface of the granite boss, are relics

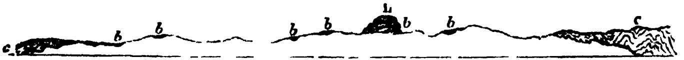

Fig. 280.—Section across part of the granite belt of the south-east of Ireland.
a, Granite; *b b*, patches of Lower Silurian rocks lying on the granite at various distances from the main Lower Silurian area, *c c*

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[1] See Jukes's 'Manual of Geology,' 3rd ed. p. 243.

of the deep cover under which the granite no doubt originally lay, and, being tougher than the latter rock, they have resisted waste so as now to cap hills and protect the granite below, as at the mountain Lugnaquilla (L in Fig. 280), which rises 3039 feet above the sea.

Recent observations by Professor Hull and Mr. Traill, of the Geological Survey of Ireland, have shown that in the Mourne Mountains, a mass of granite has in some parts risen up through highly inclined Silurian rocks, which consequently seem to be standing almost upright upon an underlying boss of granite. The strata are sharply truncated by the crystalline mass, and are indurated but not otherwise altered. The intrusive nature of the granite is well shown by the way in which numerous dykes of dark melaphyre are cut off when they reach that rock.[1] The accompanying diagram (Fig. 281) is taken from one of the sections in which this structure is portrayed by these observers.

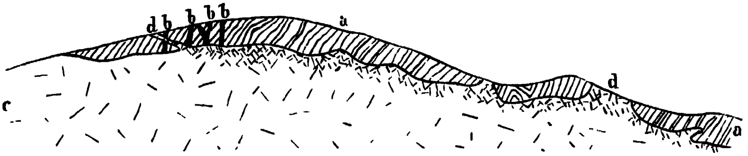

Fig. 281.—Section of Slievenamaddy, Mourne Mountains.

a a, Lower Silurian strata dipping at high angles, *b b*, Dykes of basalt (melaphyre), cutting these strata but truncated by the granite *c*, which along the outer margin and in extruded veins passes into a quartz-porphyry, *d d*.

In the Lower Silurian tract of the south of Scotland several large intrusive bosses of granite occur (Fig. 282). The strata do not dip away from them on all sides, but with trifling exceptions maintain their normal N.E and S.W. strike up to the granite on one side, and resume it again on the other. The granite indeed has not merely pushed aside the strata so as to make its way past, but actually occupies the place of so much Silurian greywacke and shale, which have disappeared, as if they had been pushed or blown out or had been melted up into the granite. There is usually a metamorphosed belt of about a mile in width, in which, as they approach the granite, the stratified rocks assume a thoroughly schistose character. Numerous small, dark, often angular patches or fragments of mica-schist may be observed in the marginal parts of the granite. Occasionally granite-veins protrude from the main masses; in the metamorphosed zone which surrounds the Criffel granite area in Kirkcudbright, hundreds of dykes and veins of various felsitic or elvanitic rocks occur (see p. 578).[2]

Similar features are presented by the granite bosses of Devon and Cornwall, which have risen through Devonian and Carboniferous strata. The Dartmoor mass is specially instructive. As shown by the early work of De la Beche, it passes across the boundary between the Devonian and Carboniferous areas, extending chiefly into the latter, so that it cuts across strata of different ages. In doing so it has risen irresistibly through the crust, without seriously affecting the general strike of the rocks. It cuts volcanic bands, as well as grits and shales into which it sends veins.[3]

Connection of Granite with Volcanic Rocks.—The manner in which some bosses of granite penetrate the rocks among which they occur strongly recalls the structure of volcanic necks or pipes (p. 584). The granite is found as a circular or elliptical mass which seems to descend vertically through the surrounding rocks without seriously disturbing them, as if a tube-shaped opening had been blown out of the crust of the earth, up which the granite had risen. Several of the granite masses of the south of Scotland, above referred to, exhibit this character very strikingly (Fig. 282). That granite and granitoid rocks have probably been associated with volcanic action is indicated by the way in which they occur in connection with the Tertiary volcanic rocks of Skye, Mull, and other islands in the Inner Hebrides. Jukes suggested many years ago that granite or granitoid masses may lie at the roots of volcanoes, and may be the source whence the more silicated lavas proceed.[1]

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[1] Horizontal Section No. 22, Geol. Surv. Ireland.

[2] Explanation of Sheet 9, Geological Survey of Scotland. The contact-metamorphism of these granite bosses is described on p. 606.

[3] De la Beche, 'Report, Devon and Cornwall,' p. 165. J. A. Phillips, *Q. J. Geol. Soc.* xxxiv. p. 493. Compare the action of the Tertiary granites of Skye, *Trans. Roy. Soc. Edin.* xxxv. (1888), Fig. 56, p. 170.

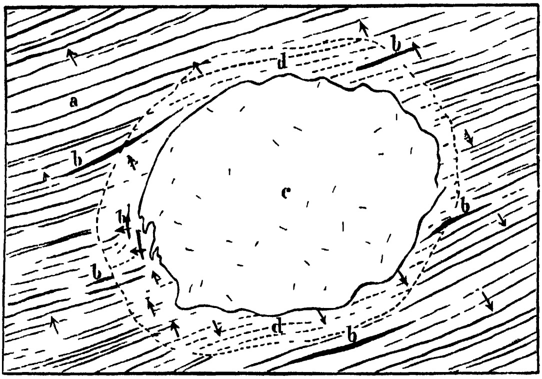

Fig. 282.—Plan of granite boss, Cairnsmore of Fleet, Scotland.

The granite area (*c*) is from 7 to 10 miles in diameter, rising through highly inclined Lower Silurian strata (*a*), among which are some conspicuous bands of black anthracitic and graptolitic shales (*b*). The arrows show the direction of dip; the parallel lines that of the strike. The ring within the dotted line round the granite defines the belt of metamorphism.

While the instances are few where any satisfactory connection can actually be traced between granitic masses and true lava-form or volcanic rocks, the close relationship between granite and the crystalline schists has long been recognised. It was formerly believed by many geologists that some granite is of metamorphic origin, that is to say, may have been produced by the gradual softening and recrystallization of other rocks at some depth within the crust of the earth. As gradations can be traced from gneiss through less distinctly crystalline schists into unaltered strata, the granite into which such gneiss seems to pass was by some looked upon as the extreme of metamorphism, the various schists and gneisses being less advanced stages of the process. Professor Dana has described a series of hornblendic, hypersthenic, augitic, micaceous, and olivine rocks in the valley of the Hudson River, which, as varieties of granite, syenite, diorite, norite, &c., he describes as masses that have been reduced to a fused or plastic condition through metamorphic action.[1] The tendency of modern inquiry is to regard granite as an eruptive and not as a metamorphic rock, and to look upon the gradations between it and various schists as phases in the deformation and alteration of the original granite. Many cases are now known where under great mechanical stresses the component minerals of granite have been drawn out, as in the fluxion structure of lavas, and the rock has assumed the laminar structure of gneiss. Many gneisses are almost certainly only varieties of granite in which a foliated structure has been superinduced.[2]

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[1] 'Manual of Geology,' 2nd ed. p. 93; Geikie, *Trans. Geol. Soc. Edin.* ii. p. 301; *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 150; Judd, *Quart. Journ. Geol. Soc.* xxx. p. 220; Reyer, *Jahrb. Geol. Reichsanst.* 1879, p. 405, and his 'Beitrag zur Physik der Eruptionen.'

Diorite, &c.—On a smaller scale usually than granite, other crystalline rocks assume the condition of amorphous bosses. Diorite, syenite, quartz-porphyry, gabbro, and members of the diabase and basalt family have often been erupted in irregular masses, partly along fissures, partly along the bedding, but often involving and apparently melting up portions of the rocks through which they have made their way. Such bosses have frequently tortuous boundary-lines, since they send out veins into or cut capriciously across the surrounding rocks. In Wales, as shown by the maps and sections of the Geological Survey, the Lower Silurian formations are pierced by huge bosses of different crystalline rocks, mostly included under the old term "greenstone," which, after running for some way with the strike of the strata, turn round and break across it, or branch and traverse a considerable thickness of stratified rock. In central Scotland, numerous masses of dolerite or diabase have been intruded among the Lower Carboniferous formations. One horizon on which they are particularly abundant lies about the base of the Carboniferous Limestone series. Along that horizon, they rise to the surface for many miles, sometimes ascending or descending in geological position, and breaking here and there abruptly across the strata.[3] There can be little doubt that they have actually melted down some parts of the stratified rocks, particularly the limestone.[4] Considerable petrographical differences occur among them, which may perhaps be in some measure due to the incorporation of such extraneous material into their mass. Gaps occur where these intrusive rocks do not rise to the surface, but as they resume their position again not far off, it may be presumed that they are really connected under these blank intervals. In the Inner Hebrides huge bosses of gabbro occur as well as granophyre and other acid rocks in the midst of the Tertiary volcanic series.

Mr. G. K. Gilbert has described, under the name of "laccolite," a structure in the Henry Mountains in Southern Utah, which is probably not uncommon in denuded volcanic districts. Large bosses of trachytic lava have risen from beneath, but instead of finding their way to the surface, have spread out laterally and pushed up the overlying strata into a dome-shaped elevation (Fig. 283). Here and there, smaller sheets proceeding from the main masses have been forced between the beds, or veins have been injected into fissures, and the overlying and contiguous strata have been considerably metamorphosed.[1]

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[1] *Amer. Journ. Sci.* xx. (1880), p. 219.

[2] See, for an early statement of this view, Dr. Lehmann's work on the granulite region of Saxony, cited *ante*, p. 156. The gneisses of the north-west of Scotland are believed to be essentially crushed and foliated eruptive rocks.

[3] *Trans. Roy. Soc. Edin.* xxix. p. 476.

[4] See Dr. Stecher's papers, quoted *postea*, pp. 601, 609.

Effects on Contiguous Rocks.—The contact-metamorphism around bosses of diorite and other rocks includes alteration of the texture and even the mineralogical composition of the rocks through which intrusive material has been erupted. The amount and nature of the change produced vary with the character and bulk of the eruptive mass, as well as with the susceptibility of the surrounding materials to alteration. Diorite, diabase, melaphyre, basalt, felsite, and other eruptive rocks are not infrequently accompanied by considerable metamorphism of the adjacent strata, though the change seldom approaches the intensity of that around large areas of granite. These phenomena are manifested also by intrusive sheets, dykes, veins, and necks. They belong to the series of changes embraced under the head of contact-metamorphism, and are grouped together for description in the next Part (p. 597).

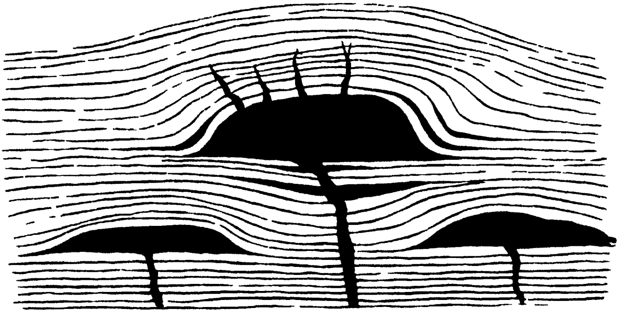

Fig. 283. - Ideal section of three "Laccolites," after Gilbert.

Effects on the Eruptive Mass.—Allusion has been made above to the displacement of rocks by eruptive bosses as if the original material that filled the present area of these bosses had been blown out, pushed up, or melted down into the advancing column of the igneous magma. If any serious amount of material were incorporated by fusion into an eruptive mass we should expect to be able to detect some change in the chemical composition or crystalline structure of the rock so affected. The observations and deductions of Dr. Stecher on the change in the composition of intrusive sheets (*postea*, p. 609) deserve full consideration, for they appear to indicate that considerable differences may be induced on an igneous mass by the incorporation into its substance of portions of the surrounding rocks.

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[1] 'Geology of the Henry Mountains,' U.S. Geog. and Geol. Survey, Washington, 1877. A similar structure was figured and described by C. Maclaren, 'Geol. of Fife and Lothians,' 1839, pp. 100, 101. The gabbros of Skye have been injected in this way into the sheets of the great basalt-plateau. *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 122. See also J. D. Dana, *Amer. Journ. Sci.* xlii. (1891), p. 79.

Connection with Volcanic Action.—There can be little doubt that in regard to eruptive masses, particularly of the dioritic, gabbro, and doleritic or basaltic series, though the portions now visible consolidated under a greater or less depth of overlying material, they must in many cases have been directly connected with superficial volcanic action. Some of them may have been underground ramifications of the ascending molten rock which poured forth at the surface in streams of lava, though these superficial portions have been removed by denudation. Others may mark the position of intruded masses which were arrested in the unsuccessful attempt to open a new volcanic vent. The gabbro and granophyre bosses of the Inner Hebrides were undoubtedly a part of the general Tertiary volcanic phenomena of that region.

Connection with Crystalline Schists.—In some regions masses of diorite, gabbro, diabase, &c., associated with crystalline schists have undergone such a rearrangement of their component minerals as to pass into amphibolites and hornblende-schists. These changes are well developed in the Saxon Granulitgebirge and in the North of Scotland. They are further referred to at pp. 182, 627.

§ 2. Sheets, Sills.

Eruptive masses have been intruded between other rocks, and now appear as more or less regularly defined beds. In many cases, it will be found that these intrusions have taken place between the planes of stratification. The ascending molten matter, after breaking across the rocks, or rather, after ascending through fissures, either previously formed or opened at the time of the outburst, has at last found its path of least resistance to lie along the bedding-planes of the strata. Accordingly it has thrust itself between the beds, raising up the overlying mass, and solidifying as a nearly or exactly parallel cake, sheet, or sill.

It is evident that one of these intercalated sheets must present such points of resemblance to a subaerial stream of lava as to make it occasionally a somewhat difficult matter to determine its true character, more especially when, owing to extensive denudation, or other cause, only a small portion of the rock can now be seen. Intrusive sheets are marked by the following characters, though these must not be supposed to be all present in every case. (1) They do not rigidly conform to the bedding of the rocks among which they are intercalated, but sometimes break across it, and run along on another platform. (2) They catch up and involve portions of the surrounding strata. (3) They sometimes send veins into the rocks above and below them. (4) They are connected with dykes or pipes which, descending through the rocks underneath, have been the channels by which the sills were supplied. (5) They are commonly most close-grained at their upper and under surfaces, and most coarsely crystalline in the central portions. (6) They are rarely cellular or amygdaloidal. (7) The rocks both above and below them are usually hardened and otherwise more or less altered.

As a well-known and (from its association with the Huttonian and Wernerian disputes) classical example of this structure, the mural escarpment called Salisbury Crags at Edinburgh may be described (Fig. 284). This is a sill of crystalline diabase (dolerite), which can be traced for a distance of 1500 yards, lying among the red and grey sandstones shales, and impure limestones, which form the base of the Carboniferous system of central Scotland. As the general dip of the rocks is north-easterly, the sill forms a lofty cliff facing west and south, from the base of which a long grassy slope of débris stretches down to the valley in front. Its thickness at the highest part is about 80 feet, but at a distance of 650 yards to the north this thickness diminishes to less than a half. At first, the diabase might be taken for a conformable sheet, regularly interposed between the sedimentary strata. But an examination of the beds on which it rests shows that it transgressively passes over a succession of platforms, and eventually comes to rest at the east end on strata somewhat lower in geological position than those at the north end. Moreover, another parallel intrusive sheet intercalated in a lower portion of the sandstone series gradually approaches the rock of Salisbury Crags. They are both transgressive across the strata, and they appear to unite in a large mass called Samson's Ribs.

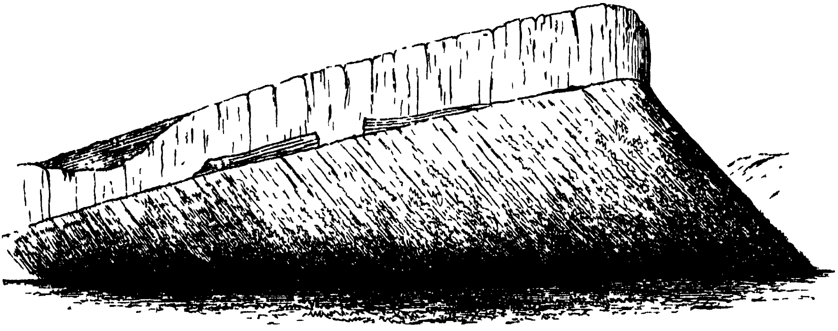

Fig. 284.—Diagrammatic view of Salisbury Crags, Edinburgh a sill in Carboniferous sandstones and shales.

On the west front, a large dyke-like mass of the diabase descends vertically through the sandstones, and has been regarded as not improbably a pipe or feeder, up which the molten rock originally rose (Fig. 284). Along the southern face of the escarpment, several instructive exposures show the behaviour of the diabase to the strata through which it has made its way. In Fig. 285, for example, a portion of the underlying strata having been carried away, the diabase has wedged itself below one of the remaining broken ends. Again, veins and threads of the eruptive rock have been

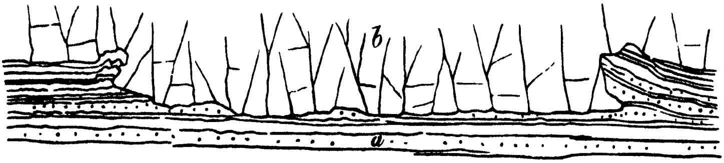

Fig. 285.—Section at base of south front of Salisbury Crags, showing portion of strata cut out by intrusive diabase. *a*, sandstones, shales, &c.; *b*, diabase. Length of section, 22 feet.

injected into fragments of the strata caught up in its mass (Fig. 286). The strata in contact with the diabase have been much hardened, the shales being converted into a kind of porcellanite, and the sandstones into quartzite.[1] The diabase in the centre of the bed is a coarse-grained rock, in which the component minerals can readily be detected with a lens, or even with the unassisted eye. But as it approaches the sedimentary beds, above and below, it becomes finely crystalline. I have had sections cut for the microscope, showing the actual junction of the two rocks (Fig. 287). In these it is interesting to observe that the diabase, for about the eighth of an inch inwards from its edge, consists mainly of an altered glass in which lie well-formed crystals of triclinic felspar and numerous opaque tufted microlites, which may be of augite. An inch back from the edge, the glass and the microlites have alike disappeared, and the rock is merely a crystalline diabase, though finer in grain than in the central portions of the bed. Numerous steam- or gas-vesicles occur in the vitreous part, some of them empty, but mostly filled with calcite or a brown ferruginous earth. There can be little doubt that

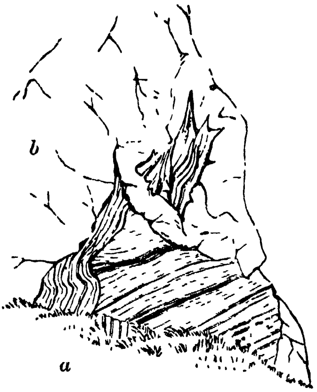

Fig. 286.

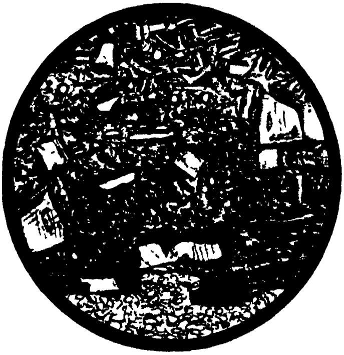

Fig. 287.

Fig 286.—Mass of sandstone and shale (*a*) imbedded in the diabase (*b*) of Salisbury Crags, and injected with veins and threads of it.

Fig. 287.—Junction of intrusive Diabase with Sandstone, Salisbury Crag, Edinburgh. Magnified 20 Diameters.—The granular portion at the bottom of the drawing is sandstone, a part of which is involved in the diabase that occupies the rest of the slide. The darker portion next the sandstone is a vitreous substance which has been serpentinized. It contains crystals of plagioclase and vapour vesicles drawn out in the direction of flow. Above the darker part the glassy condition rapidly passes into ordinary but minutely crystalline diabase. The rock has been considerably altered, calcite occupying many of the vesicles and fissures.

the vitreous structure of this marginal film was originally that of the whole rock. The thinness of the glassy crust is in harmony with all that is known as to the feeble thermal conductivity of lava. When the rock was intruded, it was no doubt a molten glass containing much absorbed vapour, the escape of which at its high temperature was probably the main agent in indurating the adjacent strata. In a number of slices cut from different parts of the central portion of the diabase, I have failed to detect any of the steam-holes so marked in the outer vitreous edge.[2]

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[1] Mr. Sorby has observed in specimens from this locality sliced by him for microscopic examination that the fluid cavities in the quartz-grains have been emptied.—Address, *Q. J. Geol. Soc.* xxxvi. Address, p. 82. But see Dr. Stecher's papers quoted p. 601. This author gives a detailed account of the contact phenomenon of the Carboniferous sills in the basin of the Firth of Forth.

[2] One of the most remarkable examples of an intrusive sheet is the Whin Sill of

This greater closeness of texture at the surfaces of contact forms one of the distinguishing marks of an intrusive as contrasted with a contemporaneous sheet (pp. 573, 590). Microscopic examination of these marginal parts from many of the intrusive sheets in central Scotland, shows that even where no distinct glass remains, the rock is crowded with black opaque microlites arranged in a delicate geometric network. Back from the surface of contact, the microlites disappear, and the magnetite or titaniferous iron assumes its ordinary crystalline and often indeterminate or imperfect contours. These bodies, developed along the marginal portions of the intrusive mass, probably belong to conditions of rapid cooling.[1]

Another lithological characteristic of the intrusive, as compared with the interbedded sheets, is the considerable variety of composition and structure which may be detected in different portions of the same mass. A rock which at one place gives under the microscope a crystalline-granular texture, with the mineral elements of diabase, will at a short distance show a coarsely crystalline texture with abundant orthoclase and free quartz—minerals which do not belong to normal diabase—or may be traversed by veins of fine-grained siliceous material. These differences, like those above referred to as noticeable among amorphous bosses, seem to point to successive stages in the consolidation of a molten magma of which the more basic constituents separated first. But sometimes they suggest that great intrusive sheets have here and there involved and melted down portions of rocks, and have thus acquired locally an abnormal composition.[2]

Effects on Contiguous Rocks.—Admirable examples of the alteration produced by eruptive masses are not uncommonly presented at the contact of intrusive sheets with the surrounding rocks. Induration, decoloration, fusion, the production of a prismatic structure, conversion of coal into anthracite, of limestone into marble, and other alterations, may be observed. The nature of these changes is described at p. 597.

Connection with Volcanic Action.—Many volcanic rocks occur in the form of intrusive sheets, as felsite, quartz-porphyry, diorite, melaphyre, diabase, dolerite, basalt, trachyte, and others. The remarks above made regarding the connection of intrusive bosses with volcanic action may be repeated with even greater definiteness here. Intrusive sheets abound in old volcanic districts, intimately associated with dykes and surface-outflows, thus bringing before our eyes traces of the underground mechanism of volcanoes. They frequently occur among the rocks that lie beneath a mass of ejected lavas and tuffs, or traverse the lower, sometimes even the upper parts of the volcanic mass. They then appear to mark some of the later stages of eruption when the orifices of discharge had become choked up and the subterranean energy only sufficed to

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Northumberland, of which an account by Messrs. Topley and Lebour will be found in *Q. J. Geol. Soc.* xxxiii. (1877), p. 406. See also J. J. H. Teall, *op. cit.* 1884.

[1] See Fouqué and Michel Lévy, 'Synthèse des Minéraux.'

[2] *Trans. Roy. Soc. Edin.* xxix. p. 492. Clough, *Geol. Mag.* 1880, p. 433. See also J. J. H. Teall, *Q. J. Geol. Soc.* xl. p. 247, xlviii. p. 104. Stecher, paper cited on p. 564.

inject the magma between the bedding of the rocks below ground but not to impel it to the surface. It is observable that later intruded masses are often more acid than the lavas previously erupted.[1]

Among the Palæozoic and Tertiary volcanic regions of Britain numerous illustrations of such sills are to be found. Some of the most striking are those that emerge from beneath the great erupted masses of Arenig and Bala age in North Wales Admirable examples occur among the Carboniferous volcanic rocks of the basin of the Forth.[2] The Tertiary sills injected among Carboniferous and Cretaceous rocks of Antrim and the Jurassic rocks of the Inner Hebrides are likewise conspicuous for size and abundance [3]

§ 3. Veins and Dykes.

The term "vein" is rather vaguely employed by geologists. It is used as the designation of any mass of mineral matter which has solidified between the separated walls of a fissure. When this mineral matter has

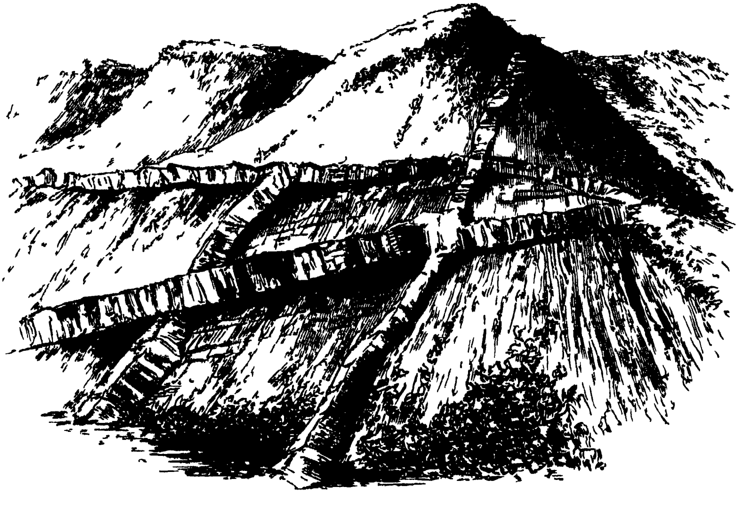

Fig 288 —Intrusive Veins and Dykes of Porphyrite in Tuff of a Volcanic "Neck, Renfrewshire

been deposited from aqueous solution or from sublimation, it forms what is known as a *mineral-vein* (p 633). When it has been injected in a molten or pasty state into some other rock, it forms an *eruptive vein*, or, if it forms a vertical wall-like mass, a *dyke*. When it forms part of the igneous rock in which it occurs, but belongs to a later period of consolidation than the portion into which it has been injected, it has been called a *contemporaneous vein*. When it has crystallized or segregated out of the component materials of some still unconsolidated, colloid, or pasty rock, it is called a *segregation-vein*.

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[1] *Trans. Roy Soc Edin* xxxv (1888), p 143 *Quart. Journ Geol Soc* xlviii (1892), Address, p 177

[2] See *Trans Roy Soc Edin* xxix. p. 474 *Op. cit.* xxxv. (1888), p 111

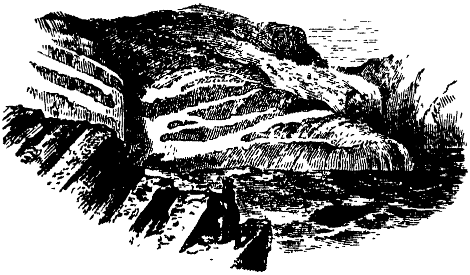

Fig. 289.—Granite Veins.

Eruptive or Intrusive Veins and Dykes are portions of once-melted, or at least pasty matter, which have been injected into rents of previously solidified rocks. When traceable sufficiently far, they may be seen to swell out and merge into their parent mass, while in the opposite direction they may become attenuated into mere threads. Sometimes they run for many yards or miles in tolerably straight lines. When this takes place along vertical or highly-inclined stratification, they look like beds, but they are of course really intrusive sheets. They may frequently be found to break across the bedding in a very irregular manner.

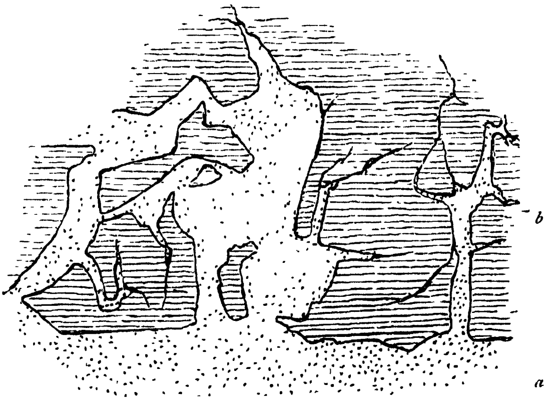

Fig. 290.—Section of granite (*a*), sending a network of veins into slate (*b*); Cornwall (*B.*)

No rock exhibits more instructively than granite the numerous varieties of form assumed by Veins.[1] Three distinct kinds of granite veins may be observed.

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[1] On granite veins, see Prof. H. Credner, *Zeitsch. Deutsch. Geol. Ges.* (1875), p. 104; (1882), p. 500. E. Kalkowsky, *op. cit.* (1881), p. 629.

1st. Protrusions of the ordinary granite extending from the main masses into the surrounding rocks and demonstrating the intrusive character of the granite (Figs. 289, 290). These varying in breadth from several feet or many yards down to fine filaments or threads, are often remarkably abundant and markedly irregular in the manner in which they branch and intersect. Where they are several yards broad their texture, at least in the central parts, may not sensibly differ from that of the main granite mass, though it is apt to become finer especially as the veins diminish in breadth. Round some bosses of granite the adjacent rocks are injected or impregnated with such an abundance of minute threads or veins of granite substance, like layers or leaves parallel with the stratification or foliation, that they are said to be "granitized."[1]

Besides greater closeness of texture, these intrusive veins sometimes present considerable differences in mineralogical composition. The mica, for example, may be reduced to exceedingly minute and not very abundant flakes, and may almost disappear. The quartz also occasionally assumes a subordinate place, and the rock of the veins passes into one of the varieties of felsite, quartz-porphyry, elvanite, aplite or eurite.[2]

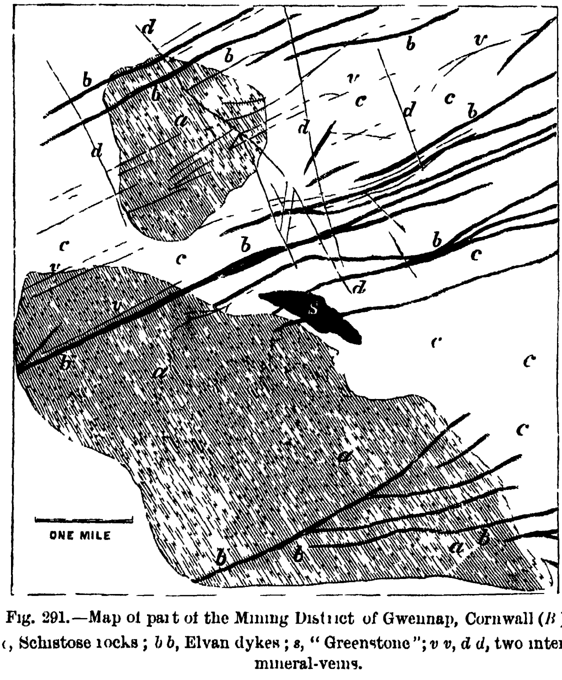

Fig. 291.—Map of part of the Mining District of Gwennap, Cornwall (*B*)
a a, Granite; *c c*, Schistose rocks; *b b*, Elvan dykes; *s*, "Greenstone"; *v v*, *d d*, two intersecting series of mineral-veins.

It is in the metamorphosed belt, already (p. 570) described as encircling an intrusive boss of granite, that eruptive veins are typically developed and most readily studied. In Cornwall, for example, the slates around the granite bosses are abundantly traversed by veins or dykes of granite and of quartz-porphyry (*elvans*), which are most numerous near the granite (Fig. 291). They vary in width from a few inches or feet to 50 fathoms, their central portions being commonly more crystalline than the sides. They frequently enclose angular fragments of slate (p. 566). In the great granite region of Leinster, Jukes traced some of the elvans for several miles running in parallel bands, each only a few feet thick, with intervals of 200 or 300 yards between them. Around some of the granite bosses of the south of Scotland similar veins of felsite and porphyry abound. The granite of the Wahsatch Mountains in Utah, which rises through the Upper Carboniferous limestones, converting them into white marble, sends out veins of granite-porphyry and other crystalline compounds. In short, all over the world it is common for eruptive bosses of this rock to have a fringe of intrusive veins (*Apophyses*).

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[1] Michel Levy, *Bull. Soc. Géol. France*, ix. (1881), p. 187, and *postea*, p. 604.

[2] See a reference to the Bodegang, *ante*, p. 159; also Hawes, *Amer. Journ. Sci.* xxi. (1881), p. 244.

(2) Veins in the granite itself. These must be regarded as later than the rock which they traverse, but they may represent lower, still liquid portions of the granitic magma which have been forced by earth-movements into rents in the partially or wholly solidified granite. They are generally finer in grain than the granite around them, and differ more or less from it also in composition, especially in their greater acidity (Fig. 30).

(3) Pegmatites. These are distinguished by the manner in which their component minerals, notably the quartz and felspar, are intergrown (see p. 98). Much discussion has arisen as to the origin of such veins. They evidently cut the ordinary granite and in so far may be regarded as intrusive veins. But it is difficult to conceive that they could have been injected in their present crystalline condition. They may have been squeezed up from some lower, still liquid part of the granitic magma, but their remarkable crystalline structure would seem to have been afterwards superinduced by some process of segregation or re-arrangement and crystallization of their materials.

Many other eruptive rocks (diorite, diabase, melaphyre, basalt, &c.) present admirable examples of intrusive (even pegmatitic) veins. These are generally distinguished from those of granite by the much less metamorphism with which they are attended.

The "Contemporaneous Veins" of older writers included those veins in crystalline rocks which though differing sufficiently from the surrounding material to be easily distinguished, resembled it so closely as to indicate that they were probably a part of it. The veins above described under No. 2 are examples. But they are not confined to granite, since they may not infrequently be observed in sheets of gabbro, diorite, dolerite, diabase, and other eruptive rocks. They are more particularly to be seen in sills and bosses. They run as straight, curved, or branching ribands, usually not exceeding a foot in thickness. They are finer in texture than the rock which they traverse. Close examination of them shows that, instead of being sharply defined by a definite junction line with the enclosing rock, they are welded into that rock in such a way that they cannot easily be broken along the plane of union. This welding is found to be due to the mutual protrusion of the component crystals of the vein and of the surrounding rock—a structure sometimes admirably revealed under the microscope. Veins of this kind evidently point to some process whereby, into rents formed in the deeply buried and at least partially consolidated or possibly pasty or jelly-like mass, there was an injection of similar material from some still unsolidified part of the mass with a transfusion or exosmosis of some of the crystallizing minerals along the mutual boundaries. Such veins are to be distinguished from the true Segregation-veins, which are irregular bands usually of more coarsely crystalline material not infrequently to be seen in intrusive sheets, wherein the constituent minerals have crystallized out in a much more conspicuous form than in the main mass of the surrounding rock along certain lines or around particular centres. These are probably due to some kind of segregation from the surrounding mass, though the conditions under which it took place have not yet been satisfactorily explained.[1] Segregation-veins occur among the crystalline schists and even in sedimentary rocks which have been crushed and metamorphosed, as in the felspathic Torridon Sandstone of Loch Carron.

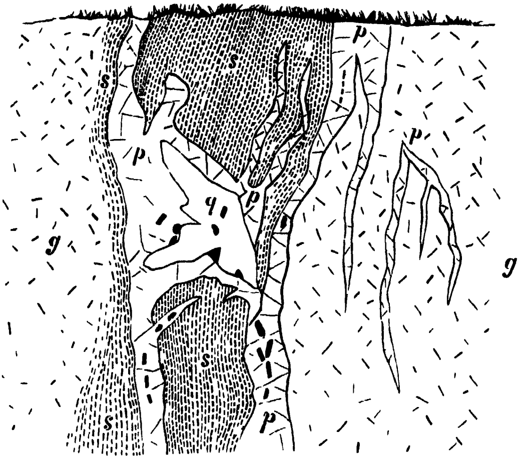

Fig. 292.—Pegmatite Vein associated with foliated granite. Rubislaw Quarry, Aberdeen. *g g*, Ordinary granite of the mass; *p p*, coarse pegmatite veins; *s s*, foliated granite passing insensibly into *g*; *q*, mass of quartz. The black patches in *p* and *q* are nests of schorl.

Along the margin of segregation-veins in granite a foliated structure of the rock may be occasionally observed, as in some of the large granite quarries near Aberdeen (Fig. 292). Coarse pegmatite veins abounding in large plates of muscovite, black tourmaline, and quartz, with occasional crystals of beryl and other minerals, merge into the surrounding granite which for a few inches along the contact has a foliated structure precisely resembling that of a fine gneiss. This foliation may indicate motion of the granite mass along the line of fissure, while the rock itself or the

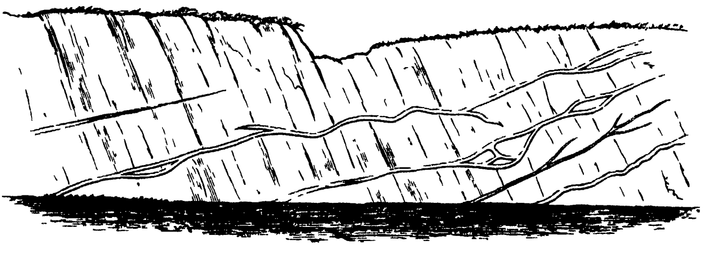

Fig. 293.—"Contemporaneous Veins" in diabase.

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[1] For some illustrations see *Trans. Roy. Soc. Edin.* xxxv. (1888), pp. 113, 115, 118, 131.

material forced up into the fissure was still capable of molecular rearrangement. It is in veins in granite that the remarkable structure known as *graphic granite* occurs.[1]

Dykes are veins of eruptive rock, filling vertical or highly-inclined fissures, and are so named on account of their resemblance to walls (*Scotice*, dykes). Their sides are often as parallel and perpendicular as those of built walls, the resemblance to human workmanship being heightened by the numerous joints which, intersecting each other along the face of a dyke, remind us of well-fitted masonry. Where the surrounding rock has decayed, the dykes may be seen projecting above ground exactly like walls (Fig. 294); indeed, in many parts of the west of Scotland they are made use of for enclosures. The material of the dykes has in other cases decayed, and deep ditch-like hollows are left to mark their sites. The coast lines of many of the Inner Hebrides and of the Clyde Islands furnish numerous admirable examples of both kinds of scenery.

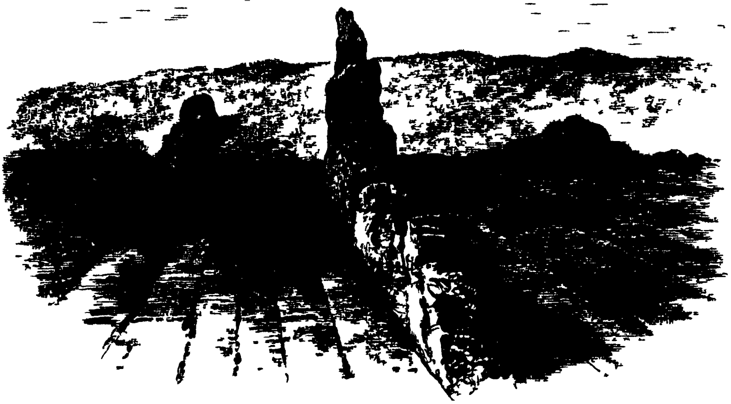

Fig. 294.—Dykes in volcanic tuff of a 'neck,' shore, Elie, Fife.

The term dyke may be applied to some of the wall-like intrusions of quartz-porphyry, elvanite, and even of granite, but it is more typically illustrated among the basic and intermediate igneous rocks such as basalt, diabase, andesite, diorite, &c., while occasionally dykes may be observed of even tuff and volcanic agglomerate.[2] Veins have been injected into irregular branching cracks; dykes have been formed by the welling upwards of liquid or plastic rock in vertical or steeply inclined fissures, though obviously there is no essential difference between the two forms of structure. Sometimes the line of escape has been along a fault. In Scotland, however, which may be regarded as a typical region for this kind of geological structure, the vast majority of dykes rise along joints or fissures which have no throw, and are therefore not faults. On the contrary, the dykes may be traced undeflected across some of the largest faults in the midland counties.

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[1] For an able discussion of Pegmatite veins see Prof. W. C. Brogger's great work 'Die Mineralien der Syenitpegmatitgange,' in Groth's *Zeitsch. Krystallographie*, xvi (1890); at p. 215 *et seq.* a historical *résumé* of the discussion will be found

[2] Some remarkable examples of sandstone-dykes have been described from various districts of North America, ranging from a mere film to eight feet broad and varying from 200 yards to upwards of nine miles in length. They have been ascribed to the infilling of

Dykes differ from veins in the greater parallelism of their sides, their verticality, and their greater regularity of breadth and persistence of direction. They sometimes occur as mere plates of rock not more than an inch or two in thickness, at other times they attain a breadth of twelve fathoms or more. The smaller or thinner dykes can seldom be traced more than a few yards; but the larger examples may be followed sometimes for many miles. Thus, in the south and west of Scotland, a remarkable series of basalt and andesite dykes can be traced across all the geological formations of that region, including the older Tertiary basalt-plateau. They run parallel to each other in a general north-west and south-east direction for distances of twenty and thirty miles, increasing in numbers towards the north-west, and they have been assigned to the great volcanic activity of Tertiary time. A dyke of the same series crosses the north of England, from near the coast of Yorkshire for about 100 miles inland. A complex system of massive pre-Cambrian dykes occurs in N.W. Scotland.

Though the wall-like form is predominant among dykes, it may readily pass into vein-like ramifications and intrusive sheets (Figs. 284, 288). The molten material took the channels that happened to be most available. If the fissure bent off at an angle from its previous trend, or if another adjacent fissure happened to be more convenient, the eruptive rock might change its course. Again, while the ascending lava, under the hydrostatic pressure of the mass below, rose in one main fissure, portions of it might find their way into neighbouring parallel rents, and enclose wall-like portions of rock within the dyke, as in Fig. 295, where the total breadth of the main dyke, including the sandstone between the two arms, is about thirty feet, the sandstone being gently inclined, and the portions enclosed between the arms of the dyke having been greatly indurated.

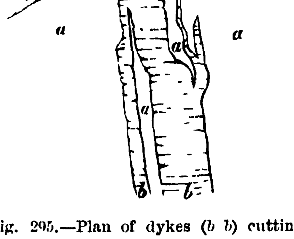

Fig. 295.—Plan of dykes (*b b*) cutting sandstone (*a a*); shore, Gourock, Renfrewshire.

It must be kept in mind, however, that irregular expansions and contractions of dykes may sometimes be caused by subsequent movements of the terrestrial crust. The dykes, for instance, may be plicated together

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fissures with sand from below by earthquakes acting on wet sandstone strata underground. J. S. Diller, *Bull. Geol. Soc. America*, i. (1890), p. 411.

with the rocks among which they have been intruded, and the folds may afterwards be pressed in such a way as to give rise to alternate or irregularly distributed enlargements and constrictions, or a similar effect may be produced by shearing or by faulting.[1] Mr. Clough has found that in a great system of dykes traversing the crystalline schists of Argyllshire frequent attenuations of the dykes are produced by faults.

In internal structure, considerable differences may be detected among dykes. The rock may appear (*a*) with no definite structure of any kind beyond irregular jointing; (*b*) columnar, the prisms striking off at right angles from the walls, and either going completely across from side to side, or leaving a central non-columnar part in which they branch and lose themselves; when the side of a dyke having this structure is laid bare, it presents a network of polygonal joints formed by the ends of the prisms which, if the dyke is vertical, lie of course in a horizontal position, whence they depart in proportion as the dyke is inclined: occasionally the prisms are as well-formed as in any columnar bed of basalt; (*c*) jointed parallel with the walls, the joints being sometimes so close as to cause the rock to appear as if it consisted of a series of vertical plates or strata: this platy character is due doubtless to contraction in cooling between parallel walls, and when it occurs in basalt-dykes is best developed near the margins; (*d*) vesicular or amygdaloidal, lines of minute vesicles having been formed parallel with the walls, and attaining their greatest number and size along the centre of the dyke.

As a rule, the outer parts of a dyke of crystalline rock, like the upper and under surfaces of an intrusive sheet, are finer grained than the centre. Occasionally, the external surface has a vitreous structure. Basalt veins, for example, have not infrequently an external coating or crust of glass (tachylite, hyalomelan, &c.) It occasionally happens also that the central portions of a basalt or andesite dyke are glassy, of which structure several cases have been observed in Scotland; perhaps in these instances the dyke has opened along its centre, and a fresh uprise of more glassy material has risen in the fissure.[2]

Effects on Contiguous Rocks.—These are similar to the changes produced by intrusive sheets and other eruptive masses. Induration is the most frequent kind of alteration. Remarkable examples have been observed where limestones in contact with dykes have had a saccharoid crystallization of the calcite superinduced upon them, and where even new crystalline silicates have been developed (pp. 320, 602).[3]

§ 4. Necks.

Under this term are included the filled-up pipes or funnels of former volcanic vents. Every series of volcanic sheets poured out at the surface must have been connected either with fissures, or with orifices probably opened in lines of fissures. On the cessation of the eruptions, these orifices have remained filled with lava or with fragmentary matter. But unless subsequent denudation has removed the overlying cone, a vent lies buried under the materials which came out of it. So extensive, however, has been the waste of the surface in many old volcanic regions that the vents have been laid bare. In Fig. 296 two volcanic funnels are represented, one of them still buried under overlying formations, the other partially exposed by denudation. The study of volcanic Necks brings before us some of the more deep-seated phenomena of volcanic action, that cannot usually be seen at a modern volcano.

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[1] Compare the structure illustrated by Fig. 312. See also Harker, *Geol. Mag.* 1889, p. 69, and the account of the pre-Cambrian rocks in Book VI. Part I.

[2] See *Proc. Roy. Phys. Soc. Edin.* vol. v. 1880, p. 241.

[3] On the Mechanism of Dykes see Mallet, *Q. J. Geol. Soc.* xxxii. (1876), p. 472.

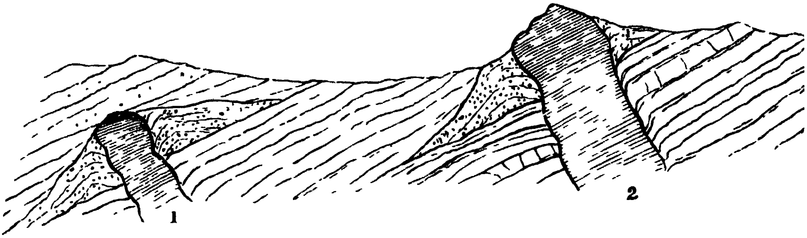

Fig. 296. Diagram-section to show the structure of old volcanic vents, and how they may be concealed and exposed.

1, Tuff cone with basalt plug still buried under sedimentary accumulations; 2, Tuff cone and basalt plug partially exposed by denudation.

A Neck is circular or elliptical in ground-plan, but occasionally more irregular and branching, and may vary in diameter from a few yards (Fig. 297) up to two miles, or even more. It descends into the earth perpendicularly to the stratification of the formation with which it is chronologically connected. Should rocks originally horizontal be subsequently tilted, a neck associated with them would of course be thrown out of the vertical (Fig. 296). As a rule, however, the vertical descent of necks into the earth's crust appears to have been comparatively little interfered with. In external form, necks commonly rise as cones or dome-shaped hills (Fig. 298). This contour, however, is not that of the original volcanoes, but is due to denudation. Occasionally the rocks of a neck have been so worn away that a great hollow, suggestive of the original crater, occupies their site. (Fintry Hills, Stirlingshire.)[1]

It might be supposed that necks should always rise on lines of fissure. But in central Scotland, where they abound in rocks of Carboniferous age, it is quite exceptional to find one placed on a fault. As a rule, they seem to be independent of the structure of the visible part of the crust through which they rise.

The materials filling up ancient volcanic orifices may be (*a*) some form of lava, as granophyre, felsite, gabbro, diabase, porphyrite, basalt;

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[1] For some striking views of denuded volcanic necks see Captain Dutton's Report on Mount Taylor and the Zuñi Plateau, *6th Ann. Rep. U.S. Geol. Survey*, 1884-85. Compare also *Trans. Roy. Soc. Edin.* vol. xxxv. (1888), p. 100.

or (*b*) the fragmentary materials which fell back into the throat of the volcano and finally solidified there. In many instances, both kinds of rock occur in the same neck, the main mass consisting of agglomerate or tuff with a central pipe or numerous veins of lava. Among the Palæozoic volcanic districts of Britain, necks not infrequently are filled with some siliceous crystalline rock, such as a quartz-porphyry or felsite, even where the surrounding lavas are basic. The great vent of the Braid Hills near Edinburgh, belonging to the time of the Lower Old Red Sandstone, is filled with felsite-tuff containing 70 per cent of silica, while the lavas which flowed from it are porphyrites and diabases with not more than 50 per cent of this acid. Again, at Largo in Fife, strings of quartz-felsite occur in one of the necks, though all the surrounding lavas are basalts.[1]

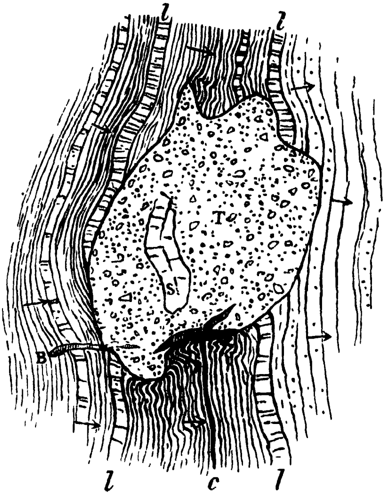

Fig. 297.—Plan of Neck, shore, near St. Monans, Fife. *l l*, beds of limestone; *c*, thin coal-seam; B, basalt veins; S, large bed or block of sandstone. The Neck, T, measures about 60 by 37 yards. The arrows mark the dip of the strata.

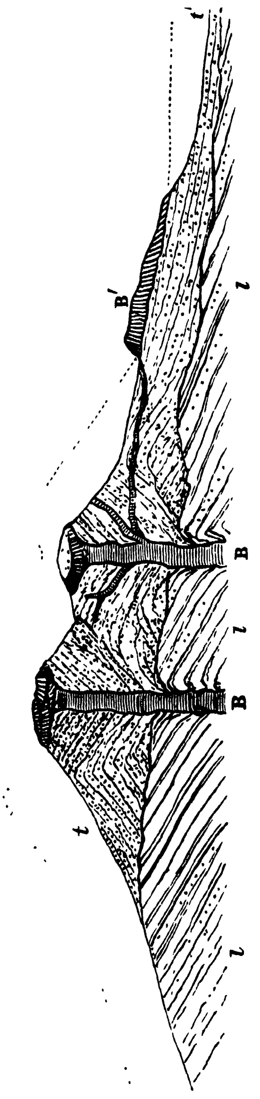

Fig. 298.—Section of the volcanic neck of Largo Law, Fife. *l*, Lower Carboniferous strata; *t*, tuff of cones; *t′*, tuff of area around the cones; B B, basalt filling central pipes of the vents and latera veins; B′, basalt, which may have flowed out at the surface. The dotted lines are suggestive of the original outline of the hill.

In some necks composed of eruptive rock, the material appears arranged in successive spherical shells, which may be supposed to be due to the protrusion of successive portions of the pasty or viscous mass one within the other, the outer layers thinning away over the crown of the dome as they were attenuated by the ascent of fresh material from below.[1] Or we may suppose that the top of the plug sometimes solidified, and that subsequent emissions of lava rose through rents in the crust, and flowed down the outside of the vent.

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[1] Necks of agglomerate and fine tuff abound among the Carboniferous and Permian volcanic regions of Scotland, and are laid bare in so many admirable sections, that these regions may be regarded as typical for this kind of geological structure.

The fragmentary materials in necks consist mainly of different lava-form rocks imbedded in a gravelly *peperino*-like matrix of more finely comminuted débris of the same rocks; but they also contain, sometimes in abundance, fragments of the strata through which the necks have been drilled. When occasionally, as in some of the Maare of the Eifel, these non-volcanic fragments constitute most of the débris (p. 244), we may infer that after the first gaseous explosions, the activity of the vent ceased, without the rise of the lava-column or its ejection in dust and fragments to the surface. So unchanged are many of the pieces of sandstone, shale, limestone, or other stratified rock in the necks, that they have evidently never been exposed to any high temperature. In some cases, however, considerable alteration is displayed. Dr. Heddle, from observations in Fife, concluded that the altered blocks in the tuff there must have been exposed to a temperature of between 660° and 900° Fahr.[2]

Among the numerous vents of Central Scotland, pieces of fine stratified tuff not infrequently appear in the agglomerates. This fact, coupled with the not uncommon occurrence of a tumultuous, fractured, and highly-inclined bedding of the tuff with a dip towards the centre of the neck (Figs. 298, 299), appears to show that the pipes were partly filled up by the subsidence of the tuff consolidated in beds within the crater and at the upper part of the funnel. Further indication of the probable subaerial character of the tuff is furnished by abundant pieces of enclosed coniferous wood, which may have belonged to trees or brushwood that grew upon the dry slopes of the cones; for these fragments are seldom to be seen in the estuarine and marine strata, out of which the necks rise.

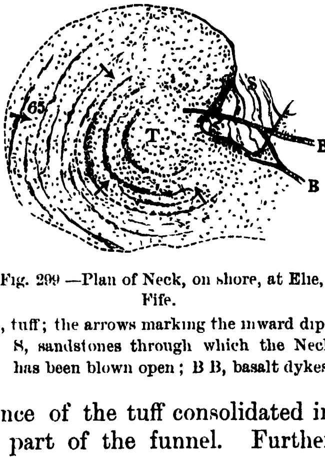

Fig. 299.—Plan of Neck, on shore, at Elie, Fife.

T, tuff; the arrows marking the inward dip, S, sandstones through which the Neck has been blown open; B B, basalt dykes.

It is common to find among necks of tuff numerous dykes and veins of lava which, ascending through the tuff, are usually confined to it, though occasionally they penetrate the surrounding strata. They are often beautifully columnar, the columns diverging from the sides of the dykes and being frequently curved.

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[1] Scrope, 'Geology and Extinct Volcanoes of Central France,' 2nd edition, p. 68. See E. Reyer, *Jahrb. Geol. Reichsanst.* xxix. (1879), p. 463; and *ante*, p. 247; A. G. *Trans. Roy. Soc. Edin.* xxxv. (1888), p. 161.

[2] *Trans. Roy. Soc. Edin.* xxviii. p. 487.

Proofs of subsidence round the sides of vents may often be observed. Stratified rocks, through which a volcanic funnel has been opened, commonly dip into it all round, and may even be seen on edge, as if they had been dragged down by the subsidence of the materials in the vent. Beautiful examples occur along the shores of the Firth of the Forth,[1]

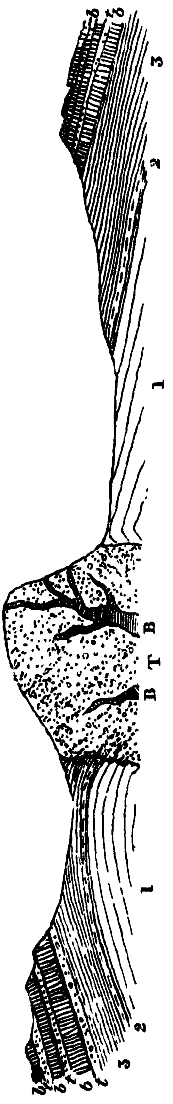

Fig. 300.—Section across the Binn of Burntisland, Fife.

1, Sandstones; 2, Limestone; 3, Shales, &c., *b b* Interstratified basalts; *t t*, Bedded tuffs, &c.; T, Tuff of the great neck of the Binn; B, Basalt veins.

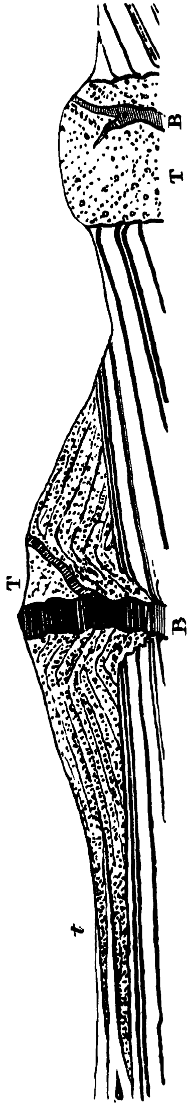

Fig. 301.—Section across the Saline Hills, Fife.

T, Tuff of necks; *t*, Continuation of tuff of cone intercalated with the contemporaneously formed sedimentary strata; B, Basalt. The thick parallel lines are coal-seams, which have been charred round the smaller eminence (Knock Hill), while they can be worked for some way under the larger, or Saline Hill.

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[1] *Trans. Roy. Soc. Edin.* xxix. p. 469. For an excellent example from New Zealand, see Heaphy, *Q. J. Geol. Soc.* 1860, p. 245.

(Figs. 300, 301). The fact of subsidence beneath modern volcanic cones has been already referred to (pp. 231, 244).

Effects on Contiguous Rocks.—The strata round a neck are usually somewhat hardened. Sandstones have acquired a vitreous lustre; argillaceous beds have been indurated into porcellanite; coal-seams have been fused, blistered, burnt, and rendered unworkable. The coal-workings in Fife and Ayrshire have revealed many interesting examples of these changes, which may be partly due to the heat of the ascending column of molten rock or ejected fragments, partly to the rise of heated vapours, even for a long time subsequently to the volcanic explosions. Proofs of a metamorphism, probably due to the latter cause, may sometimes be seen within the area of a neck. Where the altered materials are of a fragmentary character, the nature and amount of this change can best be estimated. What was originally a general matrix of volcanic dust has been converted into a crystalline and even porphyritic mass, through which the dispersed blocks, though likewise intensely altered, are still recognisable. Such blocks as, from the nature of their substance, must have offered most resistance to change—pieces of sandstone or quartz, for example—stand out prominently in the altered mass, though even they have undergone more or less modification, the sandstone being converted into vitreous quartz-rock.[1]

Section ii. Interbedded, Volcanic, or Contemporaneous Phase of Eruptivity.

Masses of igneous materials, ejected to the surface in some of the forms now visible in modern volcanoes, possess great value as fixing the geological epoch of volcanic eruptions. It is evident that, on the whole, such superficial masses must agree in lithological characters with rocks already described, which have been extravasated by volcanic efforts without quite reaching the surface. Yet they have some well-marked general characters, of which the most important may be thus stated. (1) They occur as beds or sheets, sometimes lava-form, sometimes of fragmental materials, which conform to the bedding of the strata among which they are intercalated. (2) They do not break into or alter overlying strata. (3) The upper and under surfaces of the lava-beds present commonly a scoriaceous or vesicular character, which may even be found extending throughout the whole of a sheet. (4) Fragments of these upper surfaces not unusually occur in the immediately overlying strata. (5) Beds of tuff are frequently interstratified with sheets of lava, but may also occur by themselves, interstratified among ordinary sedimentary strata.

§ 1. Crystalline, or Lavas.

While the underground course of a protruded mass of molten igneous rock has widely varied according to the shape of the channel through which it proceeded and in which, as in a mould, it solidified, the behaviour of the rock, once poured out at the surface, has been much more uniform. As in modern lava, the erupted mass has rolled along, varying in thickness and other minor characters, but retaining the broad general aspect of a lenticular bed or sheet. A comparison of such a bed with one of the intrusive sheets already described shows that in several important lithological characters they differ from each other. An intrusive sheet is closest in grain near its upper and under surfaces. A contemporaneous bed or true lava-flow, on the contrary, is there usually most open and scoriaceous. In the one case, we rarely see vesicles or amygdales, in the other they often abound. However rough the upper surface of an interbedded sheet may be, it never sends out veins into, nor encloses portions of, the superincumbent rocks, which, however, sometimes contain portions of it, and wrap round its hummocky irregularities. Occasionally it may be observed to be full of rents, which have been filled up with sandstone or other sedimentary material. These rents were formed while the lava was cooling, and sand was subsequently washed into them. Examples of this structure abound among the porphyrites of the volcanic tracts of the Scottish Lower Old Red Sandstone. The amygdaloidal cavities throughout an interbedded sheet, but more especially at the top, often present an elongated form, and are even pulled out into tube-like hollows in one general direction, which was obviously the line of movement of the yet viscous mass (pp. 102, 227). Some kinds of rock, when occurring in interbedded sheets, are apt to assume a system of columnar jointing. Basalt, in particular, is distinguished by the frequency and perfection of its columns. The Giants' Causeway, the cliffs of Staffa, of Ardtun in Mull, and of Loch Staffin in Skye, the Orgues d'Expailly in Auvergne, and the Kirschberg of Fulda are well-known examples.

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[1] For a detailed account of the structure of some volcanic necks, the student may consult a monograph by the author on the Carboniferous volcanic rocks of the Basin of the Forth, *Trans. Roy. Soc. Edin.* xxix. p. 437.

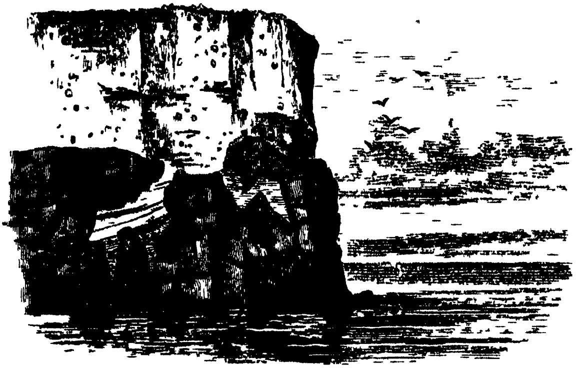

Fig 302.—Sandstone filling rents in the surface of an interbedded sheet or flow of porphyrite, which is covered with a bed of conglomerate. Coast of Kincardineshire.

The rents have been filled in with sand before the eruption of the next flow.

Interbedded lavas of former geological periods, like those of recent date (*ante*, p. 239), occur under two tolerably well-defined conditions.

1. Lenticular sheets or groups of sheets, usually of limited extent and with associated bands of tuff, form the more frequent type among Palæozoic and Secondary formations. A single interbedded sheet may occasionally be found intercalated between ordinary sedimentary strata, without any other volcanic accompaniment. But this is unusual. In the great majority of cases, several sheets occur together, with accompanying bands of contemporaneous tuff.

In such abundantly volcanic districts as central Scotland, the necks or vents of eruption (p. 584) may frequently be detected around the lavas which proceeded from them. The thickness of an interbedded sheet varies for different kinds of lava. As a rule, the more acid rocks are in thicker beds than the more basic. Some of the thinnest and most persistent sheets may be observed among the basalts, where a thickness of not more than 12 or 15 feet for each sheet is not uncommon. Both individual sheets and groups of sheets possess a markedly lenticular character. They may be seen to thicken in a particular direction, probably that from which they flowed. Thus in Linlithgowshire a mass of lavas and tuffs, reaching a collective thickness of probably 2000 feet in the Carboniferous Limestone series, rapidly dies out, until within a distance of only ten miles it dwindles down to a single band less than fifty feet thick. On the other hand, beds of tolerably uniform thickness and flatness of surface may be found; among the basalts, more particularly, the same sheet may be traceable for miles, with remarkable regularity of thickness and parallelism between its upper and under surfaces (p. 226). The porphyrites (Fig. 303) and trachytic and felsitic lavas are more irregular in thickness and form of surface (p. 222).

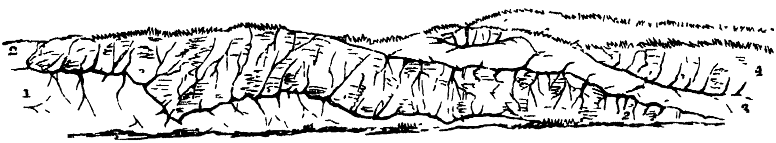

Fig. 303.—Four successive flows of porphyrite, Lower Carboniferous, East Linton.

Abundant examples of this type of volcanic extrusion may be studied among the Palæozoic and Tertiary formations of Western Europe, and nowhere on a larger scale than in the British Isles. The Cambrian lavas and tuffs of Pembrokeshire, and those of Arenig and Bala age in North Wales, the Lake District, the south of Scotland, and the south-east of Ireland, form a notable record of volcanic activity in older Palæozoic time. They were succeeded by the great outpourings of the Old Red Sandstone, Devonian, Carboniferous, and Permian volcanoes. But the volcanic energy gradually diminished until the last Carboniferous and Permian eruptions gave rise to *puys* like those of Auvergne, never discharging such voluminous floods of lava as those of earlier periods, and probably in many cases emitting only showers of ashes and stones.[1] There appears to have been a complete quiescence of volcanic activity during the whole of the Mesozoic ages in Britain. But the subterranean fires were rekindled in older Tertiary time, and gave forth the great basalt sheets of Antrim and the Inner Hebrides.

On the continent of Europe a similar long record of volcanic action is found, with a corresponding Mesozoic quiescence. Cambrian, Silurian, Devonian, Carboniferous, and Permian volcanic rocks have been found in France. The Permian volcanic rocks of

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[1] *Quart. Journ. Geol. Soc.* (Anniv. Address), vol. xlviii. p. 147.

Germany have long been well known.[1] In the Tyrol extensive sheets of quartz-porphyry of Triassic or older date with associated tuffs occur.[2]

Interbedded (and also intrusive) sheets have shared in all the subsequent curvature and faulting of the formations among which they lie. This relation is well seen in the "toadstone" or diabase beds associated with the Carboniferous Limestone of Derbyshire (Fig. 304).[3]

2. The second type is displayed in widespread plateaux composed of many successive sheets, frequently with little or no intercalation of tuff. It occurs even among Palæozoic formations, but attains its greatest development among the volcanic eruptions of Tertiary time. Instead of mere local lenticular patches, these sheets lie piled over each other sometimes to a depth of several thousand feet, and frequently cover areas of many thousand square miles.

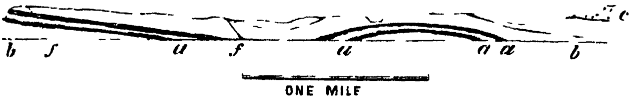

Fig. 304.—Section of intercalated diabase (toadstone) in Carboniferous Limestone, Derbyshire (*B.*) *a a*, Toadstone, in two beds; *b b*, Limestones; *c*, Millstone grit; *f f*, Faults.

Among the Palæozoic rocks of Scotland remnants of such ancient volcanic plateaux occur in the Old Red Sandstone (hills of Lorne) and Carboniferous systems (Campsie Fells and hills above Largs), where they consist chiefly of consecutive sheets of different porphyrites and diabases rising into long terraced tablelands. The regularity of thickness and parallelism of these sheets form conspicuous features in the scenery of the districts in which they occur.

It is chiefly basaltic rocks, however, that in all parts of the world have flowed out without the production of prominent cones and craters, and now build up vast volcanic plateaux. The fragmentary Miocene plateaux of the British Islands, the Faroe Islands and Iceland; those of the Indian Deccan and of Abyssinia, and the more recent basalt floods which have closed the eventful history of volcanic action in North America, are notable illustrations of this type of structure. Beds of tuff, conglomerate, gravel, clay, shale, or other stratified intercalations occasionally separate the sheets of basalt. Layers of lacustrine clays, sometimes full of leaves, and even with sufficiently thick masses of vegetation to form bands of lignite or coal, may also here and there be detected. But marine intercalations are rare or absent. There can be no doubt that these widely extended sheets of basalt were in the main subaerial outpourings, and that in the hollows of their hardened surfaces lay lakes and smaller pools of water in which the interstratified sedimentary materials were laid down. The singular persistence of the basalt-beds has often been noticed. The same sheet may be followed for several miles along the magnificent cliffs of Skye and Mull. Mr. Clarence King believes that single sheets of basalt in the Snake River lava-field of Idaho may have flowed for 50 or 60 miles.[4] The basalts, however, so exactly resemble each other that the eye may be deceived unless it can follow a band without any interruption of continuity.

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[1] References to the intercalated volcanic rocks of former geological periods will be found in the account of the geological systems in Book VI.

[2] E. Mojsisovics, 'Die Dolomit-riffe von Sudtirol,' 1879.

[3] See Section 18, 'Hor. Sec. Geol. Surv. Great Britain.'

[4] 'Geological Exploration of 40th Parallel,' i. p. 593. See also C. E. Dutton, *Nature*, 27th November 1884. *6th Ann. Rep. U.S. Geol. Surv.* 1884-85, p. 181, and *4th Ann. Rep.* of same Survey, 1882-83, p. 85.

§ 2. Fragmental, or Tuffs.

While the observer may be in doubt whether a particular bed of lava has been poured out at the surface as a true flow, or has consolidated at some depth, and, therefore, whether or not it is to be regarded as evidence of an actual volcanic outbreak at the locality, he is not liable to the same uncertainty among the fragmental eruptive rocks. Putting aside the occasional brecciated structure seen along the edges of plutonic intrusive masses, he may regard all the truly fragmental igneous rocks as proofs of volcanic action having been manifested at the surface. The agglomerate found in a volcanic neck could not have been formed unless the vapours in the vent had been able to find their way to the surface, and in so doing to blow into fragments the rocks on the site of the vent as well as the upper part of the ascending lava-column.[1] Wherever, therefore, a bed or a series of beds of tuff occurs interstratified in a geological formation, it points to contemporaneous volcanic eruptions. Hence the value of these rocks in interpreting the volcanic annals of a region.

The fragmentary ejections from a volcano or a cooling lava-stream vary from the coarsest agglomerate to the finest tuff, the coarser materials being commonly found nearest to the source of discharge. They differ in composition, according to the nature of the lavas with which they are associated and from which they have been derived. Thus, a region of trachyte-lavas supplies trachyte-tuffs and trachyte-breccias; one of basalts gives basalt-breccias, basalt-agglomerates, basalt-tuffs; one of obsidians yields pumiceous tuffs and breccias. The fragmentary matter ejected from volcanic vents has fallen partly back into the funnels of discharge, partly over the surrounding area. It is apt, therefore, to be more or less mingled with ordinary sedimentary detritus. We find it, indeed, passing insensibly into sandstone, shale, limestone, and other strata. Alternations of gravelly *peperino*-like tuff with a very fine-grained "ash" may frequently be observed. Large blocks of lava-form rock, as well as of the strata through which the volcanic explosions have taken place, occur in the tuffs of most old volcanic districts. Occasionally such ejected blocks or bombs are found among fine shales and other strata, the lamination of which is bent down round them in such a way as to show that the stones fell with considerable force into the still soft and yielding silt or clay (Fig. 305).[2]

Volcanic tuffs and conglomerates occur in interstratified beds without any accompanying lava, much more commonly than do interstratified sheets of lava, without beds of tuff; just as in recent volcanic districts, it is more usual to find cones of ashes or cinders without lava, than lava-sheets without an accompaniment of ashes. Masses of fine or gravelly tuff, several hundreds of feet in thickness, without the intervention of any lava-bed, may be observed in the volcanic districts of the Old Red Sandstone and Carboniferous systems in Scotland. These furnish evidence of long-continued volcanic action, during which fragmentary materials were showered out over the water-basins, mingled with little or no ordinary sediment. On the other hand, in these same areas, thin seams of tuff interlaminated with sandstone, shale, or limestone, afford indications of feeble intermittent volcanic explosions, whereby light showers of dust were discharged, which settled down quietly amidst the sand, mud, or limestone accumulating at the time. Under these latter circumstances, tuffs often become fossiliferous; they enclose the remains of such plants and animals as might be lying on the lake-bottom or sea-floor over which the showers of volcanic dust fell, and thus they form a connecting link between aqueous and igneous rocks.

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[1] It is conceivable that where a mass of lava was injected into a subterranean cavern, fragmentary discharges might take place and partly fill that cavity; but such exceptional cases are probably extremely rare.

[2] See *Geol. Mag.* i. (1864), p. 22.

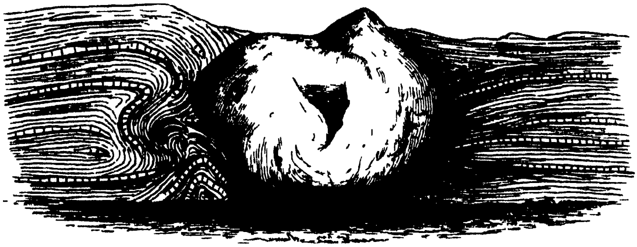

Fig. 305.—Ejected volcanic block (12 × 15 × 17 inches) in Lower Carboniferous Shales, Pettycur, Fife

As illustrations of the nature of the stratigraphical evidence for former conditions of volcanic activity, two sections from Linlithgowshire may here be given. In the first of these (Fig. 306), a black shale (1) of the usual carbonaceous type, with remains of terrestrial plants, lies at the bottom. It is covered by a bed of nodular bluish-grey tuff (2), containing black shale fragments, whence we may infer that the underlying or some similar shale was blown out from the site of the vent that furnished this dust and gravel. A second black shale (3) is succeeded by a second thin band of fine pale yellowish tuff (4). Black shale (5) again supervenes, containing rounded fragments of tuff, perhaps lapilli intermittently ejected from the neighbouring vent, and passing up into a layer of tuff (6), which marks how the volcanic activity gradually increased again. It is evident that, but for the proximity of an active volcanic vent, there would have been a continuous deposit of black shale, the conditions of sedimentation having remained unchanged. In the next stratum of shale (7), thin seams and nodules of clay-ironstone accumulated round decomposing organic remains on the muddy bottom. A brief volcanic explosion is marked by the thin tuff-bed (8), after which the old conditions of deposit continued, the bottom of the water, as the shale (9) shows, being crowded with ostracod crustaceans, while fishes, whose coprolites have been left in the mud, haunted the locality. At last, however, a much more powerful and prolonged volcanic explosion took place. A coarse agglomerate or tuff (10), with blocks sometimes nearly a foot in diameter, was then thrown out and overspread the lagoon.

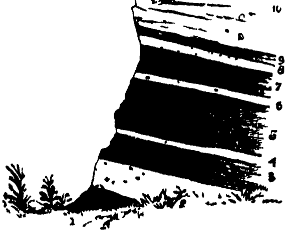

Fig. 306.- Section of interstratifications of tuff and shale, Old Quarry, Wester Ochiltree, Linlithgowshire (Lower Carboniferous).

The second example (Fig. 307) brings before the mind a volcanic episode of another kind, in the history of the same region. At the bottom of the section, a pale amygdaloidal, somewhat altered form of basalt (A) marks the upper surface of one of the submarine lavas of the Carboniferous Limestone period. Directly over it comes a bed of limestone (B) 15 feet thick, the lower layers of which are made up of a dense growth of the thin-stemmed coral, *Lithostrotion irregulare*, which overspread the hardened lava. The next stratum is a band of dark shale (C), about 2 feet thick, followed by about the same thickness of an impure limestone with shale seams. The conditions for coral growth were evidently not favourable; for the deposit of this argillaceous limestone was arrested by the precipitation of a dark mud, now to be seen in the form of 3 or 4 inches of a black pyritous shale (E), and next by the inroad of a large quantity of a dark sandy mud, and drift vegetation, which has been preserved as a sandy shale (F) containing *Calamites*, *Producti*, ganoid scales, and other traces of the terrestrial and marine life of the time. Finally a sheet of lava, represented by the uppermost amygdaloid (G), overspread the area, and sealed up these records of Palæozoic history.[1]

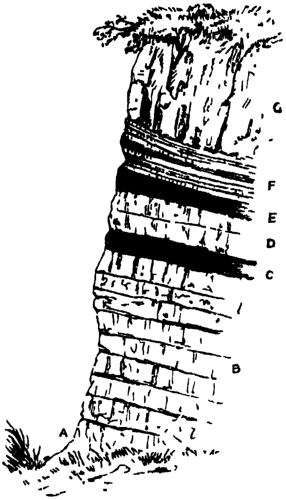

Fig. 307.—Section in Wardlaw Quarry, Linlithgowshire.

PART VIII. METAMORPHISM, LOCAL AND REGIONAL.

At the outset some caution must be employed as to the use of the terms "metamorphism" and "metamorphic." It is obvious that we have no right to call a rock metamorphic, unless we can distinctly trace it into an unaltered condition, or can show from its internal composition and structure that it has undergone a definite change, or can prove its identity with some other rock whose metamorphic character has been satisfactorily established. Further, it must be remembered that, in a certain sense, all or nearly all rocks may be said to have been metamorphosed, since it is exceptional to find any, not of very modern date, which do not show, when closely examined, proofs of having been hardened by the pressure of superincumbent rock, and altered by the action of percolating water or other daily acting agent of change. Even a solid crystalline mass, which, when viewed on a fresh fracture with a good lens, seems to consist of unchanged crystalline particles, will often betray under the microscope unmistakable evidence of alteration. And this alteration may go on until the whole internal organisation of the rock, so far at least as we can penetrate into it, has been readjusted, though the external form may still remain such as hardly to indicate the change, or to suggest that any new name should be given to the recomposed rock. Among many igneous rocks,

[1] See 'Memoirs of Geol. Survey, Geology of Edinburgh,' pp. 45, 58. *Trans. Roy. Soc. Edin.* xxix. p. 483.

particularly the more basic kinds (diabases, basalts, andesites, diorites, olivine rocks, &c.), alteration of this nature may be studied in all stages.[1]

But mere alteration by decay is not what geologists denote by metamorphism. The term has been, indeed, much too loosely employed: but it is now generally used to express a change in the mineralogical or chemical composition and in the internal structure of rocks, produced at some depth from the surface, through the operation of mechanical movement, combined with the influence of heat and heated water or vapour. A metamorphic rock may be more compact and crystalline than the parent mass from which it has been derived, like which, also, when exposed at the surface, it again undergoes alteration by weathering.

Various kinds of metamorphism have been distinguished by special names;[2] but they may be included in three main groups. 1st, change of texture, including the induration and other minor phenomena of "contact-metamorphism"; 2nd, change of form, including all paramorphic transformations, such as the conversion of a pyroxenic into a hornblendic rock, and the alteration of a clastic into a crystalline mass by the crystallization of its original constituents; 3rd, change of substance, where a chemical change has been superinduced either by the abstraction or addition of one or more ingredients, as in the remarkable contact zones round certain intrusive bosses. It is obvious, however, that each of these three kinds of metamorphism may be included in the changes which have been superinduced upon a given mass of rock.

The conditions that appear to be mainly concerned in metamorphism have been already stated (p. 319). It may be added here that these conditions may in different cases be supplied: 1st, by the action of heated subterranean water carrying carbonic acid and mineral solutions (p. 305); 2nd, by the action of hot vapours and gases upon underground rocks (pp. 228, 305, 589); 3rd, by mechanical movements, particularly those which have resulted in the crushing and shearing of rocks (p. 311); 4th, by the intrusion of heated eruptive rocks, sometimes containing a large proportion of absorbed water, vapours, or gases (pp. 230, 568, 572, 576); 5th, occasionally and very locally by the combustion of beds of coal.

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[1] See Index, *sub voc.* "Weathering."

[2] For instance, *metasomatosis*, *metasomatic*, *methylosis*, *methylotic*, and *metachemic* applied to chemical metamorphism or alteration of constitution or substance; *metastasis*, indicating changes of a paramorphic nature; *metacrasis*, denoting such transformations as the conversion of mud into a mass of mica, quartz, and other silicates; *macro-structural* metamorphism, having the external structure (morphology) changed, as where an amorphous condition becomes schistose; *micro-structural*, having the internal structure (histology) wholly changed, with or without a macro-structural alteration; *mineralogical*, having one or more of the component minerals changed, with or without an alteration of the chemical composition of the rock as a whole. See King and Rowney "An old Chapter of the Geological Record," 1881; Dana, *Amer. Journ. Sci.* xxxii. (1886), p. 69. Bonney, *Quart. Journ. Geol. Soc.* (1886), Address, p. 30 *et seq.* G. H. Williams, *Bull. U.S. Geol. Surv. No.* 62 (1890), p. 43. Various terms have likewise been proposed for metamorphism from the point of view of its cause, as *Dislocation-metamorphism* (Lossen), *Mechanical metamorphism* (Heim and Baltzer), *Dynamical metamorphism* (Rosenbusch), *Heaping-up metamorphism* (*Stauungs M.* Credner), *Pressure metamorphism* (Bonney).

When the term "metamorphism" was originally proposed by Lyell it applied to rocks having a schistose or foliated structure which were regarded as altered sediments. For many years afterwards it continued to be used in the same sense, and not until comparatively recently did geologists recognise that rocks originally of eruptive origin but interposed among sedimentary strata, were necessarily affected by the changes which the latter underwent in the processes of metamorphism. It is now well established that igneous rocks no less than aqueous have been metamorphosed, and, as Lossen has pointed out, they furnish in some respects even a better starting-point from which to attack the problem of metamorphism, inasmuch as their original definite mineral aggregation, chemical composition, and structure furnish a scale by which the subsequent mutations of the rocks may be traced and measured.[1]

Metamorphism is manifested in two distinct phases. 1st, Local (the metamorphism of contact or of juxtaposition), where the change has been effected only within a limited area, round some eruptive mass, beyond which the ordinary condition of the altered rocks can be seen. 2nd, Regional, where the change has taken place over a large tract without reference to visible eruptive masses, the original characters of the altered rocks being more or less completely effaced. Between the results of local and regional metamorphism, no sharp line can be drawn; they insensibly graduate into each other and may arise from one common cause.

§ i. **Local Metamorphism** (metamorphism of contact or juxtaposition).

In this kind of alteration two fundamental conditions have to be considered: 1st, the nature, mass, temperature, and composition of the eruptive rock; and 2nd, the composition and structure of the rocks through which the intrusive material has been injected. With regard to the first of these conditions, it is obvious that a large intrusion will produce more alteration than a small intrusion of the same rock. The areole of metamorphism round a great boss of granite or of diorite will be broader and the metamorphism itself more intense than round a mere vein or dyke. But the case is different when we compare intrusions of altogether unlike materials. The temperature of granite appears to have been comparatively low (p. 308). We never meet with cases of fusion round even the largest bosses of granite; carbonate of lime is not deprived of its carbonic acid. But the injections of intermediate and basic rocks give proofs of far more elevated temperatures. Dykes of andesite or basalt may often be observed to have baked argillaceous rocks into porcellanite, and to have actually fused the rocks in contact with them. But in these instances the alteration is confined within limits of a few inches or feet. The metamorphism induced round a boss of granite, on the other hand, may extend for a breadth of a mile or more. Much of the change in the latter case may be ascribed to the influence of the mineralizing agents with which the granite was impregnated (see p. 308).

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[1] *Jahrb. Preuss. Geol. Landesanst.* 1884, p. 620. See also, for an early study of the influence of contact-metamorphism on augitic igneous rocks, Allport, *Q. J. Geol. Soc.* xxxii. (1876), p. 418.

With respect to the influence of the nature and structure of the altered rock upon the metamorphism, it is obvious that such different materials as shale, sandstone, coal, and limestone, will give very different results even if exposed to the same amount and kind of metamorphic energy. And much will depend also upon the relation between the position of the intrusive mass and the stratification of the rocks affected. As stated on p. 52, heat is conducted four times faster along the planes of stratification than across them, so that an intruded sheet or sill should, other things being equal, produce less alteration than a boss which breaks across the bedding.

The following examples of the nature of the metamorphism of contact are arranged in progressive order of intensity, beginning with the feeblest change, and ending with results that are quite comparable with the great changes involved in regional metamorphism.

Bleaching is well seen at the surface, where heated volcanic vapours rise through tuffs or lavas and convert them into white clays (p. 233). Decoloration, however, has proceeded also, underneath, along the sides of dykes. Thus in Arran, a zone of decoloration ranging from 5 or 6 to 25 or 30 feet in width, runs in the red sandstone along each side of many of the abundant basalt-dykes. This removal of the colouring peroxide may have been effected by the prolonged escape of hot vapours from the cooling lava of the dykes. Had it been due merely to the reducing effect of organic matter in the meteoric water filtering down each side of the dyke, it ought to occur as frequently along joints in which there has been no ascent of igneous matter.

Coloration.—Rocks, particularly shale and sandstone, in contact with intrusive sheets, are sometimes so reddened as to resemble the burnt shale from an ironwork. Every case of reddening along a line of junction between an eruptive and non-eruptive rock must not, however, be set down without examination as an effect of the mere heat of the injected mass, for sometimes the colouring may be due to subsequent oxidation of iron in one or both of the rocks by water percolating along the lines of contact.

Induration.—One of the most common changes superinduced upon sedimentary rocks along their contact with intrusive masses, is a hardening of their substance. Sandstone, for example, is converted into a compact rock which breaks with the lustrous fracture of quartzite. Argillaceous strata are altered into flinty slate, Lydian-stone, jasper, or porcellanite. This change may sometimes be produced by mere dry heat, as when clay is baked. But probably, in the majority of cases, induration of subterranean rocks results from the action of heated water. The most obvious examples of this action are those wherein the percentage of silica has been increased by the deposit of a siliceous cement in the interstices of the stone, or by the replacement of some of the mineral substances by silica. This is specially observable round eruptive masses of granite and diabase.[1]

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[1] Kayser, on contact-metamorphism around the diabase of the Harz, *Z. Deutsch. Geol.*

Expulsion of Water.—One effect of the intrusion of molten matter among the ordinary cool rocks of the earth's crust has doubtless often been temporarily to expel their interstitial water. The heat may even have been occasionally sufficient to drive off water of crystallization or of chemical combination. Mr. Sorby mentions that it has been able to dispel the water present in the minute fluid cavities of quartz in a sandstone invaded by diabase.[1]

Prismatic Structure.—Contact with eruptive rocks has frequently produced a prismatic structure in the contiguous masses. Conspicuous illustrations of this change are displayed in sandstones through which dykes have risen (Fig. 308). Independently of the lines of stratification, polygonal prisms, six inches or more in diameter, and several feet in length, starting from the face of the dyke, have been developed in the sandstone.[2]

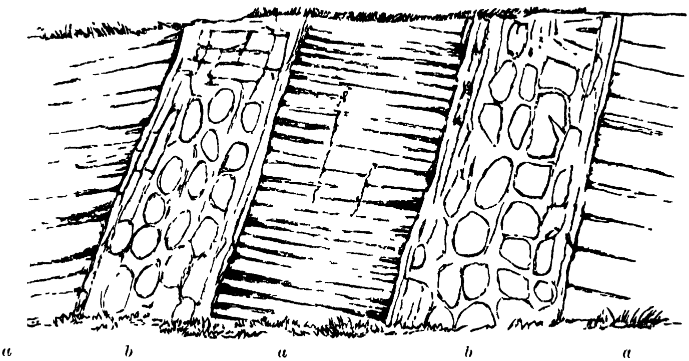

Fig. 308.—Sandstone (*a a*) rendered prismatic by Dolerite (*b b*); Bishopbriggs, Glasgow.

Some of the most perfect examples of superinduced prisms may occasionally be noticed in seams of coal which have been invaded by intrusive igneous rocks. In the Scottish coal-fields, sheets of basalt have been forced along the surfaces of coal-seams, and even along their centre, so as to form a bed or sheet in the middle of the coal-seam. The coal in these cases is sometimes beautifully columnar, its slender hexagonal and pentagonal prisms, like rows of stout pencils, diverging from the surface of the intrusive sheet.[3]

Ges. xxii. 103, where analyses showing the high percentage of silica are given. Hawes, *Amer. Journ. Sci.* January 1881. The phenomena of metamorphism round granite are further described below, p. 605 *seq.*

[1] *Q. J. Geol. Soc.* 1880. *Ante*, p. 575.

[2] Sandstone altered by basalt, melaphyre, or allied rock, Wildenstein, near Budingen, Upper Hesse, Schöberle, near Kriebitz, Bohemia; Johnsdorf, near Zittau, Saxony (the Quader-sandstone of Gorischstein, in Saxon Switzerland, is beautifully columnar; W. Keeping, *Geol. Mag.* 1879, p. 437); Bishopbriggs, near Glasgow.

[3] Coal and lignite, with their accompanying clays, altered by basalt, diabase, melaphyre, &c., Ayrshire, Scotland; St. Saturnin, Auvergne; Meissner, Hesse Cassel; Ettingshausen, Vogelsgebirge; Sulzbach, Upper Palatinate of Bavaria; Funfkirchen, Hungary: by trachyte, Commentry, Central France; by phonolite, Northern Bavaria.

Other examples of the production of this structure have been described in dolomite altered by quartz-porphyry (Campiglia, Tuscany); fresh-water limestone altered by basalt (Gergovia, Auvergne); basalt-tuff and granite altered by basalt[1] (Mt. Saint-Michel, Le Puy).

Calcination, Melting, Coking.[2]—By the great heat of erupted masses, more especially of basalt and its allies, rocks have been calcined and partially or completely melted. In some, the matrix or some of the component minerals have been melted; in others the whole rock has been fused. Among granite fragments ejected with the slags of old volcanic vents in Auvergne, some present no trace of alteration, others are burnt as if they had been in a furnace, or are partially melted so as to look like slags, each of their component minerals, however, remaining distinct. In the Eifel volcanic region, the fragments of mica-schist and gneiss ejected with the volcanic detritus have sometimes a crust or glaze of glass. Sandstones, though most frequently baked into a compact quartzite, are sometimes changed into an enamel-like mass in which, when the rock contains an argillaceous or calcareous matrix with dispersed quartz-grains, the infusible quartz may be recognised (Oberellenbach, Lower Hesse). According to Bunsen's observations, volcanic tuff and phonolite have sometimes been melted for several feet on the sides of the dolerite dykes which traverse them, so as to present the aspect of pitchstone or obsidian.[3] Besides complete fusion and fluxion-structure there has sometimes been also a production of microscopic crystallites in the fused portions, resembling those of eruptive rocks.

The effects of eruptive rocks upon carbonaceous beds, and particularly upon coal-seams, are among the most conspicuous examples of this kind of alteration. In a coal-field much invaded by igneous rocks, seams of coal are usually found to have suffered more than the other strata, not merely because they are specially liable to alteration from the proximity of heated surfaces, but because they have presented lines of more easy escape for the igneous matter pressed from below. The molten rock has very generally been injected along the coal-seams; sometimes taking the lower, sometimes the upper surface, or even, as already stated, forcing its way along the centre.

The alterations produced by the intrusion vary considerably, according to the bulk and nature of the eruptive sheet, the thickness, composition, and structure of the coal-seam, and probably other causes. In some cases, the coal has been fused and has acquired a blistered or vesicular texture, the gas cavities being either empty or filled with some infiltrated mineral, especially calcite (east of Fife). In other examples, the coal has become a hard and brittle kind of anthracite or "blind coal," owing to the loss of its more volatile portions (west of Fife). This change may be observed in a coal-seam 6 or 8 feet thick, even at a distance of 50 yards from a large dyke. Traced nearer to the eruptive mass, the coal passes into a kind of pyritous cinder, scarcely half the original thickness of the seam. At the actual contact with the dyke, it becomes by degrees a kind of caked soot, not more perhaps than a few inches thick (South Staffordshire, Ayrshire). Coal altered into a prismatic substance has been above (p. 599) referred to; it has even been changed into graphite (New Cumnock, Ayrshire, see Fig. 301).

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[1] Naumann, 'Geognosie,' i. p. 737.

[2] It is worthy of observation that changes of the kind here referred to occur most commonly with basalt-rocks, melaphyres, and diabases. Trachyte has been a less frequent agent of alteration, though some remarkable examples of its influence have been noted. Poulett Scrope (*Geol. Trans.* 2nd ser. ii.) describes the alteration of a trachyte conglomerate by trachyte into a vitreous mass. Quartz-porphyry and diorite occasionally present examples of calcination, or more or less complete fusion. But with the granitic and syenitic rocks changes of this kind have never been observed. Naumann, 'Geognosie,' i. p. 744.

[3] Usually the vitreous band at the margin of a basalt dyke belongs to the intruded rock and not to that through which it has risen (see "Basalt-glass." *ante*, pp. 171, 584).

Striking as is the change produced by the intrusion of basalt into coals and bituminous shales, it is hardly more conspicuous than the alteration effected on the invading rock. A compact crystalline black heavy basalt or diabase, when it sends sheets and veins into a coal or highly carbonaceous shale, becomes yellow or white, earthy, and friable, loses weight, ceases to have any apparent crystalline texture, and, in short, passes into what would at first unhesitatingly be pronounced to be mere clay. It is only when the distinctly intrusive character of this substance is recognised in the veins and fingers which it sends out, and in its own irregular course in the altered coal, that its true nature is made evident. Microscopical examination shows that this "white-rock" or "white-trap" is merely an altered form of some diabasic or basaltic rock, wherein the felspar crystals, though much decayed, can yet be traced, the augite, olivine, and magnetite being more or less completely changed into a mere pulverulent earthy substance.[1] Traces of the glassy selvage of contact may still sometimes be detected in these altered rocks. The changes in the constitution of an igneous mass, owing to the surrounding rocks, is referred to at p. 571.

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[1] The following analyses show the composition of these "white rock-traps." No. I., by Henry, is from the South Staffordshire coal-field ('The South Staffordshire Coal-Field,' in *Mem. Geol. Survey*, p. 118); No. II., by E. Stecher, is from Newhalls, Queensferry, Linlithgowshire. (*Tschermak's Mittheil.* ix. (1887), p. 190. *Proc. Roy. Soc. Edin.* 1888, p. 172. These memoirs of Dr. Stecher give an account of the contact phenomena round the intrusive diabases of the Carboniferous series in the basin of the Firth of Forth.)

	I.	II.
Silica . . .	38·830	36·8
Alumina . .	13·250	22·95
Lime . . .	3·925	9·73
Magnesia . . .	4·180	2·85
Soda . . .	0·971	0·5
Potash . .	0·422	1·1
Iron protox. . .	13·830	4·08 FeO
Iron perox. . .	4·335	2·6 TiO_2
Carbonic acid . .	9·320	11·9 0·75 P_2O_5
Water . . .	11·010	7·7
	100·073	100·96

The basalt of Meissner (Lower Hesse) overlies a thick stratum of brown coal which shows an interesting series of alterations. Immediately under the igneous rock, a thin seam of impure earthy coal ("letten") appears as if completely burnt. The next underlying stratum has been altered into metallic-lustred anthracite, passing downwards into various black glossy coals, beneath which the brown coal is worthless. The depth to which the alteration extends is 5·3 metres.[1] Another example of alteration has been described by G. vom Rath from Fünfkirchen in Hungary.[2] A coal-seam has there been invaded by a basic igneous rock (perhaps diabase) now so decomposed that its true lithological character cannot be satisfactorily determined. Here and there, the intrusive rock lies concordantly with the stratification of the coal, in other places it sends out fingers, ramifies, abruptly ends off, or occurs in detached nodular fragments in the coal. The latter, in contact with the intrusive material, is converted into prismatic coke. The analysis of three specimens of the coal throws light on the nature of the change. One of these (A) shows the ordinary composition of the coal at a distance from the influence of the intrusive rock ; the second (B), taken from a distance of about 0·3 metre (nearly 1 foot), exhibits a partial conversion into coke ; while in the third (C), taken from immediate contact with the eruptive mass, nearly all the volatile hydrocarbons have been expelled.

	Ash.	Sulphur.	Coke.	Bitumen.
A.	8·29 per cent.	2·074	79·7	20·3
B.	9·73 ,,	1·112	87·8	12·2
C.	45·96 ,,	0·151	95·3	4·7

During the subterranean distillation arising from the destruction or alteration of coal and bituminous shales, while the gases evolved find their way to the surface, the liquid products, on the other hand, are apt to collect in fissures and cavities. In central Scotland, where the coal-fields have been so abundantly pierced by igneous masses, petroleum and asphaltum are of frequent occurrence, sometimes in chinks and veins of sandstones and other sedimentary strata, sometimes in the cavities of the igneous rocks themselves. In West Lothian, intrusive sheets, traversing a group of strata containing seams of coal and oil-shale, have a distinctly bituminous odour when freshly broken, and little globules of petroleum may be detected in their cavities. In the same district, the joints and fissures of a massive sandstone are filled with solid brown asphalt, which the quarrymen manufacture into candles.

Marmarosis.—The conversion of ordinary dull granular limestone into crystalline or saccharoid marble may not infrequently be observed on a small scale, where an intrusive sheet or dyke has invaded the rock. It is also observable as a general phenomenon, apart from the appearance of visible eruptive rocks, and in such cases serves to unite local and regional metamorphism. In zones of contact-metamorphism round granite and other eruptive bosses many minerals have crystallized out in the altered limestone, such as tremolite, zoisite, and garnet.

One of the earliest described examples of this change is that at Rathlin Island, off the north coast of Ireland (Fig. 309). Two basalt dykes (20 and 35 feet thick respectively) ascend there through chalk, of which a band 20 feet thick separates them. Down the middle of this central chalk band runs a tortuous dyke one foot thick. The chalk between the dykes and for some distance on either side has been altered into a finely granular marble.[1] On the east side of the great intrusive mass of Fair Head the chalk is likewise marmarised. Another smaller but interesting illustration of the same change occurs at Camps Quarry near Edinburgh. The dull grey Burdie House limestone (Lower Carboniferous), full of valves of *Leperditia* and plants, has there been invaded by a basaltic dyke, which, sending slender veins into the limestone, has enclosed portions of it. The limestone is found to have acquired the granular crystalline character of marble, each little granule of calcite having its own orientation of cleavage planes (Fig. 310).

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[1] Moesta, 'Geologische Schilderung, Meissner und Hirschberge,' Marburg, 1867.

[2] G. vom Rath, *N. Jahrb.* 1880, p. 276. In the above analysis the bitumen includes all volatile constituents driven off by heat, hence coke and bitumen = 100. Another instance is described by Gümbel from Mährisch-Ostrau, where coal is coked by an augite-porphyry, *Verh. Geol. Reichsanst.* 1874, p. 55.

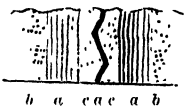

Fig. 309.—Dykes of basalt (*a a a*) traversing chalk (*b b*), which near the dykes is converted into marble (*c c*), Rathlin Island, Antrim.

Production of New Minerals.—One of the results of the intrusion of eruptive rock has been the development of crystalline minerals in ordinary sedimentary strata near the line of contact. The new minerals have usually an obvious affinity in composition with the original rock. But undoubtedly silica has often been introduced as part of the alteration, either free or as silicates. Moreover, a certain broad order of succession in the appearance of these new minerals may be observed in the larger areas of contact-metamorphism. On the outer margin of the ring or areole of metamorphism the internal re-arrangements and mineralogical re-combinations show themselves in many argillaceous rocks by the appearance of small knots or concretions which are replaced further inward by recognisable silicates, such as chiastolite, andalusite, staurolite, or kyanite, while towards the centre the dark mica which appears even in the outer parts of the ring attains a marked prominence, often accompanied with garnets and other new minerals.

A simple but interesting instance of this kind of contact-metamorphism was described many years ago by Henslow, near Plas Newydd, Anglesea. A basalt dyke, 154 feet in breadth, there traverses strata of shale and argillaceous limestone, which are altered to a distance of 35 feet from the intrusive rocks, the limestone becoming granular and crystalline, and the shale being hardened, here and there porcellanized, while its shells (*Producti*, &c.), though nearly obliterated, are still traceable by their impressions. In the altered fossiliferous shale numerous crystals of analcime and garnet have been developed, the latter yielding as much as 20 per cent of lime.[2] Similar phenomena were observed by Sedgwick along the edges of intruded basalt among the Carboniferous limestones and shales of High Teesdale.[3]

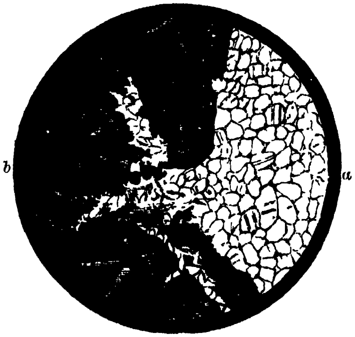

Fig. 310.—Section of limestone (*a*) (Burdie House) converted into granular marble by basalt (*b*). Magnified 20 diameters.

In Hesse and Thuringerwald, Zirkel has described sandstones altered by contact with basalt, where the quartz-grains are enveloped in a vitreous matrix, in which abundant microscopic microlites occur, and present in their arrangement evidence of a fluxion-structure. This glassy constituent probably represents the argillaceous and other materials in which the quartz-grains were originally imbedded, and which has been fused and made to flow by the heat of the basalt.[1]

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[1] Conybeare, *Trans. Geol. Soc.* iii. p. 210 and plate X. One of the most remarkable examples of marmarosis is the alteration of the (Triassic) limestone of Carrara into the well-known statuary marble (see *postea*, p. 629).

[2] *Cambridge Phil. Trans.* i. p. 402.

[3] *Op. cit.* ii. p. 175.

Among localities where the development of new minerals in proximity to eruptive rock has taken place on the most extensive scale, none have been more frequently or carefully described than some in the group of mountains lying to the east and south-east of Botzen, in the Tyrol (Monzoni, Predazzo). Limestones of Lower Triassic (or Permian) age have there been invaded by masses of monzonite (a rock intermediate between syenite and diorite, sometimes containing much augite), granite, melaphyre, diabase, and orthoclase-porphyry. They have become coarsely-crystalline marble, portions of them being completely enveloped in the eruptive rock. But their most remarkable feature is that in them, and in the eruptive rocks in contact with them, many minerals often beautifully crystallized, have been developed, including garnet, idocrase, gehlenite, fassaite, pistacite, spinel, anorthite, mica, magnetic iron, hæmatite, apatite, and serpentine. Some of these minerals occur chiefly or only in the eruptive masses, others more frequently in the limestone, which is marked by a lime-silicate hornstone zone along the junction. But these are all products of contact of the two kinds of rock. Layers of carbonates (calcite, also with brucite) alternate with laminæ and streaks of various silicates, in a manner strikingly similar to the arrangement found in limestones among areas of regional metamorphism, where no visible intrusive rock has influenced the phenomena.[2]

Production of Foliation.—This is the most complete kind of metamorphic change, for not only are new minerals developed, but the whole texture and structure of the rock are altered. Reference has been already (p. 568 *seq.*) made to the striking manner in which foliation has been superinduced upon ordinary sedimentary rocks round large bosses of granite. The details of this change deserve careful consideration, for they possess a high importance in relation to any theory of metamorphism.

In some cases (and probably these are more frequent than has been suspected) there has been a copious injection of granitic material not merely as large veins or dykes, but in minute threads and laminæ into the surrounding rock, following generally the more marked divisional planes, such as those of bedding, cleavage, or foliation. This impregnation or granitization has been strongly insisted upon by M. Michel Lévy and has been noticed by other observers.[3] Near the contact of the micaceous schists of Saint Léon with the granite which pierces them, the distinguished French geologist found that the eruptive rock has been injected between the planes of the schists in leaves from a few millimetres to one or two centimetres thick, the rock has thus a ribboned appearance from the alternation of numerous dark micaceous layers with the finely granular pink or white veins from the granite. By such a process of metamorphism and injection sedimentary strata have acquired a structure that can hardly be distinguished from that of some ancient gneisses.[1]

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[1] *N. Jahrb.* 1872, p. 7. For other examples see Mohl, *Verhandl. Geol. Reichsanst.* 171, p. 259; Hussak, *Tschermak's Min. Mittheil.* 1883, p. 530.

[2] On the Monzoni region, see Doelter, *Jahrb. Geol. Reichsanstalt*, 1875, p. 207, where a bibliography of the locality up to the date of publication will be found. Other papers have since appeared, of which the following dealing with the phenomena of contact-metamorphism may be mentioned. G. vom Rath, *Z. Deutsch. Geol. Ges.* 1875, p. 343; 'Der Monzoni in sudostlichen Tirol,' Bonn, 1875; Lemberg, *Z. Deutsch. Geol. Ges.* 1877, p. 457.

[3] Michel Lévy, *Bull. Soc. Géol. France*, ix. (1881) p. 187, (1888) p. 221. *Compt. rend. International Geol. Congress*, 1888. I have myself studied similar cases of injection among the schists around the granites near Lairg in Sutherland, and others have lately been worked out in detail by Messrs. Peach and Horne in the Geological Survey of the north-eastern part of the same county.

Round the granite bosses of Devon and Cornwall, already referred to (*ante*, p. 569), the Devonian and Carboniferous formations have undergone remarkable changes, which have long been cited as classic examples of contact-metamorphism. Fine greywacke and slate have been converted into mica-schist and varieties of gneiss (cornubianite). In some cases the slates become indurated and dark in colour, and new minerals (schorl, chiastolite, &c.) are developed in them. The volcanic bands intercalated with the sedimentary series likewise undergo alteration, the "greenstones," in particular, becoming much more coarsely crystalline as they approach the granite. Each boss of granite is surrounded with its ring of metamorphism, which varies greatly in breadth and in the intensity of alteration.[2]

In the Lake District of the north of England excellent examples of the phenomena of contact may be observed round the granite of Skiddaw. The alteration here extends for a distance of two or three miles from the central mass of granite. The slate, where unaltered, is a bluish-grey cleaved rock, weathering into small flakes and pencil-like fragments. Traced towards the granite, it first shows faint spots, which increase in number and size until they assume the form of chiastolite crystals, with which the slate is now abundantly crowded. The zone of this chiastolite-slate seldom exceeds a quarter of a mile in breadth. Still closer to the granite, a second stage of metamorphism is marked by the development of a general schistose character, the rock becoming more massive and less cleaved, the cleavage-planes being replaced by an incipient foliation due to the development of abundant dark little rectangular or oblong spots, probably imperfectly crystallized chiastolite, this mineral, as well as andalusite, occurring also in large crystals, together with minute flakes of mica (spotted schist, Knotenschiefer). A third and final stage is reached when, by the increase of the mica and quartz-grains, the rock passes into mica-schist—a light or bluish-grey rock, with wonderfully contorted foliation, which is developed close to the granite, there being always a sharp line of demarcation between the mica-schist and the granite.[3]

In the same region the granite boss of Shap has produced some interesting changes on the andesitic and rhyolitic lavas and tuffs associated with the Lower Silurian strata. These changes have been studied by Messrs. Harker and Marr, who describe the gradual alteration of the andesites by the development of brown mica, hornblende, sphene, and other minerals. The amygdaloidal cavities had been filled with secondary products, and the rocks had thus been considerably weathered before the intrusion of the granite, for the materials filling the vesicles partake in the general metamorphism. By the gradual increase of the brown mica and the production of a marked laminated structure indicated by the parallel disposition of the mica-flakes, these lavas and tuffs assume the aspect of true crystalline schists.[1]

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[1] See Michel Lévy "sur l'origine des Terrains crystallins primitifs," *International Geol. Congress*, 1888, p. 59; and the account of pre-Cambrian rocks, *postea*, Book VI.

[2] De la Beche, 'Report on Geology of Devon and Cornwall,' *Mem. Geol. Survey*, 1839, p. 268. See also Forbes, *Trans. Geol. Soc. Cornwall*, ii. p. 260, and Boase, *op. cit.* iv. (1832), p. 166. The microscopic structure of the unaltered slates of Cornwall has been described by Allport, *Q. J. Geol. Soc.* xxxii. (1876), p. 407, and that of the greenstones by J. A. Phillips, *op. cit.* xxxiv. (1878). Some interesting observations on the metamorphism of Cornish and other slates are given by Sorby in his Address to the Geological Society, *op. cit.* xxxvi. (1880), p. 81 *et seq.*

[3] J. C. Ward, *Q. Journ. Geol. Soc.* xxxii. (1876), p. 1. Compare the development of andalusite in regional metamorphism, p. 627, note.

Farther north, in the south-western counties of Scotland, several large masses of fine-grained granite rise through the Lower Silurian greywacke and shale, which, around the granite for a variable distance of a few hundred yards to nearly two miles, have undergone great alteration (see Fig. 282). These strata are ranged in steep anticlinal and synclinal folds which run across the south of Scotland in a general north-east and south-west direction. It is observable that this normal strike continues, with little modification, up to the granite, which thus has replaced an equivalent area of sedimentary rock (see p. 570). The coarser arenaceous beds, as they approach the granite, are changed into quartz-rock, the thin siliceous shales into Lydian-stone, the black anthracitic graptolite-shales into a compact mass charged with pyrites, and breaking into large rough blocks. Strata wherein felspar-grains abound have been altered to a greater distance than the more siliceous beds, and show a gradation through spotted schists, with an increasing development of mica and foliation, until along the edge of the granite they become true mica-schist and even a fine kind of gneiss.[2] The pebbly conglomerates which form a marked horizon among the unaltered rocks, are traceable in the metamorphosed areole as rocks which, at first sight, might be taken for some kind of porphyritic gneiss. Their quartz-pebbles have assumed a resinous aspect, and are enveloped in a crystalline micaceous paste. The metamorphism of the Highlands is referred to on pp. 625, 698.

A classical region for the study of contact-metamorphism is in the Harz, where, round the granite masses of the Brocken and Ramberg, the Devonian and older Palæozoic rocks are altered into various flinty slates and schists which form a ring round the eruptive rock. Dykes and other masses of a crystalline diabase have likewise been erupted through the greywackes and shales, which in contact and for a varying distance beyond, have been converted into hard siliceous bands (hornstone) and into various finely foliated masses (fleckschiefer, bandschiefer, contactschiefer, the spilosite and desmosite of Zincken). The limestones have their carbon-dioxide replaced by silica in a broad zone of lime-silicate along the contact.[3] The black compact limestone of Haserode becomes a white saccharoid marble, charged with silicates (rhombic dodecahedrons of garnet, &c.) and with its carbonaceous matter segregated into abundant veins. A limestone band containing ironstone presents, in the Spitzenberg between Altenau and Harzburg, a garnetiferous magnetite containing well-preserved crinoid stems.[4]

Round the syenite of Meissen, in Saxony, the diabases when they come within the areole of contact-metamorphism pass into actinolite-schists and anthophyllite-schists.[5]

The French Pyrenees present instructive examples of the effect of the protrusion of granite and other eruptive rocks upon Cambrian and later formations. Fuchs has traced the metamorphism of clay-slate through spotted schists (frucht-, chiastolite-, and andalusite-schists) into mica-schist and gneiss.[1] More recently the region has been studied in great detail by Barrois, who distinguishes three successive zones in the metamorphic areola surrounding the granite. On the outside lies the zone of "goffered schists," in which a puckered structure has been developed without any new mineral combination of the elements of the rock. Next come the chiastolite-schists, with crystals of chiastolite, tourmaline, &c., which become more and more micaceous towards the interior, till they pass into the third and innermost zone, that of the leptinolites, which are highly micaceous schists with small crystals of chiastolite, and sometimes with tourmaline, rutile and triclinic felspar. Barrois also shows that round the masses of kersantite a ring of chloritic mica-schist has been developed, followed outside by one of spotted schists.[2]

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[1] Harker and Marr, *Q. J. Geol. Soc.* xlvii. (1891), p. 266.

[2] J. Horne, *Mem. Geol. Surv. Scotland,* Explanation of Sheet 9, p. 22. *Brit. Assoc.* 1892, p. 712. The microscopic structure of the altered rocks in this district has been studied by Prof. Bonney and Mr. Allport, *Proc. Roy. Soc.* xlvi. (1889), and Miss M. J. Gardiner, *Q. J. Geol. Soc.* xlvi. (1890), p. 569.

[3] Zincken, *Karsten und v. Dechen, Archiv,* v. p. 345 ; xix. p. 583. Fuchs, *N. Jahrb.* 1862, pp. 769, 929. K. A. Lossen, *Z. Deutsch. Geol. Ges.* xix. p. 509 (on the Taunus) ; xxi. p. 291 ; xxiv. p. 701. Kayser, *op. cit.* xxii. p. 103. The memoirs of Lossen form some of the most important contributions to our knowledge of the phenomena of metamorphism.

[4] K. A. Lossen, *Z. Deutsch. Geol. Ges.* xxix. 1877, p. 206. *Erläuter. Geol. Special-Kart. Preuss.* Blatt, Harzgerode (1882).

[5] K. Dalmar, Blatt 64 (Tanneberg) *Erläuter. Special-Kart. Sachsen* (1889) ; A. Sauer, *op. cit.* Blatt 48 (Meissen).

Some important observations have been made by Barrois at Guéméné, in the maritime department of Morbihan, where Lower Silurian strata have been invaded by granite. Of special interest are the effects produced upon the sandstones (grès à scolithes), which are converted into micaceous quartzites. These altered rocks, traced farther inwards, are further distinguished by the development in them of sillimanite, sometimes in sufficient abundance to impart a foliated, undulated, gneissoid structure. At the contact with the eruptive rock, this quartzite shows recrystallized quartz, black mica, sillimanite, cordierite, and a good many crystals of orthoclase and plagioclase, besides white mica. The conglomerates show their matrix altered into a mass composed of rounded or angular grains of quartz united by abundant white sericitic mica, and containing some crystals of zircon, large plates of muscovite, and yellow granules of limonite.[3]

Another admirable locality for the study of contact-metamorphism is the eastern Vosges. Rosenbusch, in describing the phenomena there, has shown that the unaltered clay-slates are grey, brown, violet, or black, thinly fissile, here and there curved, crumpled, and crowded with kernels and strings of quartz.[4] Traced towards the granite of Barr Andlau, they present an increasingly pronounced metamorphism. First they assume a spotted appearance, owing to the development of small dark points and knots, which increase in size and number towards the granite, while the ground-mass remains unaltered (knotenschiefer, fruchtschiefer). The ground-mass of the slate then becomes lighter in colour, harder, and more crystalline in appearance, while flakes of mica and quartz-grains make their appearance. The knots, now broken up, rather increase than diminish in size; the hardness of the rock rapidly increases, and the fissile structure becomes unrecognisable on a fresh fracture, though observable on a weathered surface. Still nearer the granite, the knot-like concretions disappear from the rock, which then has become an entirely crystalline mass, in which, with the lens, small flakes of mica and grains of quartz can be seen, and which under the microscope appears as a thoroughly crystalline aggregate of andalusite, quartz, and mica. The proportions of the ingredients vary, but the andalusite and quartz usually greatly preponderate (andalusite-schist). Chemical analysis shows that the unaltered clay-slate and the crystalline andalusite-schist next the granite consist essentially of similar chemical materials, and that

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[1] *N. Jahrb.* 1870, p. 742; see also Zirkel, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867), p. 175.

[2] 'Recherches sur les Terrains anciens des Asturies et de la Galice,' quarto, Lille, 1882.

[3] *Ann. Soc. Géol. Nord*, xi. (1884), p. 103. Compare also the early observation of Puillon-Boblaye regarding trilobites and orthids in chiastolite slates, *Comptes rend.* vi. (1836), p. 168, confirmed by the Comte de Limur, *Bull. Soc. Géol. France* (3), xiii. (1885) p. 55.

[4] *N. Jahrb.* 1875, p. 849. 'Die Steigerschiefer und ihre Contact-Zone,' Strassburg, 1877. Unger, *N. Jahrb.* 1876, p. 785.

"probably the metamorphism has not taken place by the addition or subtraction of matter, but by another and still unknown process of molecular transposition."[1] In some cases, boric acid has been supplied to the schists at the contact.[2] Still more striking, perhaps, is the condition of the rocks at Rothau; they have become hornblendic, and their included corals have been replaced, without being distorted, by crystals of hornblende, garnet, and axinite.[3]

In the Christiania district of southern Norway, singularly clear illustrations of the metamorphism of sedimentary rocks round eruptive granite have long been known. Kjerulf has shown that each lithological zone of the Silurian formations, as it approaches the granite of that district, assumes its own distinctive kind of metamorphism. The limestones become marble, with crystals of tremolite and idocrase. The calcareous and marly shales are changed into hard, almost jaspery, shales or slates; the cement-stone nodules in the shales appear as masses of garnet; the sandy strata become hard siliceous schists (halleflinta, jasper, hornstone) or quartzite; the non-calcareous black clay-slates are converted into chiastolite-schists, or graphitic schists, but often show to the eye only trifling alteration. Other shaly beds have assumed a fine glimmering appearance; and, in the calcareous sandstone, biotite has been developed. In spite of the metamorphism, however, neither fossils nor stratification have been quite obliterated from the altered rocks. From all the stratigraphical zones fossils have been found in the altered belt, so that the true position of the metamorphosed rocks admits of no doubt.[4] Prof. W. C. Brogger has subjected the rocks of the zones of contact-metamorphism round Christiania to a searching microscopic examination, and has published a highly important and interesting memoir on the subject. He describes the unaltered and altered conditions of the more conspicuous stratigraphical bands, and thus provides new material for the investigation of contact-metamorphism. Especially interesting are his descriptions of the distinctive metamorphism of each band, the remarkably variable amount of alteration even in the same band, the persistence of recognisable graptolites even in rocks that have become essentially crystalline, the transformation of limestone into marble, of which a fourth or fifth part is composed of garnet, partly in large rhombic dodecahedrons, and partly as a mould enclosing *Orthis calligramma*.[5]

One further European example may be cited from the observations of F. E. Muller, who has described round the granite of the Hennberg near Lehesten in the Frankenwald the occurrence of knotted schists, chiastolite-schists, knotted mica-schists, and andalusitic mica-rocks.[6]

The same phenomena have been observed in many other parts of the world. One example from America may suffice to show how precisely the facts collected in the Old World are repeated in the New. An elaborate examination was made of the contact-metamorphism of the granite of Albany, New Hampshire, by the late Mr. G. W. Hawes.[7] His analyses indicate a systematic and progressive series of changes in the schists as they approach the granite. The rocks are dehydrated, boric and silicic acids have been added to them, and there appears to have been also an infusion of alkali directly on the contact. He regarded the schists as having been impregnated by very hot vapours and solutions emanating from the granite.

Alteration of the Intrusive Rock.—Reference has been made above (p. 571) to the possible alteration of composition in an eruptive mass by fusing into itself some portion of the rocks through which it is intruded, and also to the remarkable change superinduced upon intrusive sills of diabase by contact with carbonaceous strata. Dr. Stecher, to whom I sent a carefully collected series of specimens illustrative of the intrusive sheets of the basin of the Firth of Forth and their contact phenomena, has investigated this question and obtained some interesting results. He shows that along the edges of contact with the sandstones or shales these diabases present a great abundance of well-defined crystals of olivine, that as the rock is examined progressively further from the contact these crystals become more or less corroded, while in the centre of the sheet they so entirely disappear that the rock appears as a diabase without olivine. He finds that the interior parts of the mass are more acid than the exterior parts and he attributes this difference to the incorporation of silica from rocks (sandstones, &c.) broken through by the diabase. The outer olivine-bearing selvage he regards as representing the original composition of the rock at the time of its extrusion, and he thinks that the assimilation of acid material by the central still fluid and slowly cooling portion led to the corrosion and re-solution of the olivine which at the time of extrusion, as proved by the marginal selvage, was already perfectly crystallized out. In some of the rocks he found a surplus of silica which had crystallized as quartz. Recognising that the first portion to take definite crystalline form would be more basic than the still liquid portions, he yet concludes that this will not account for the observed facts, which in his opinion point to an actual addition of silica.[1] It is very desirable that similar careful chemical and microscopic investigation should be undertaken with a special view to the determination of the difference in chemical constitution between the peripheral and central portions of intrusive masses, and to ascertain whether any such difference can be traced to the influence of the rocks through which these masses have been erupted.

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[1] Unger, *op. cit.* p. 806.

[2] Rosenbusch, 'Die Steigerschiefer,' &c., p. 257.

[3] *Ann. des Mines*, 5^{me} sér. xii. p. 318.

[4] 'Geologie Norwegens,' 1880, p. 75. For the literature of the Norwegian locality see E. Reyer, *Jahrb. Geol. Reichsanst.* xxx. (1880), p. 26.

[5] 'Die Silurischen Etagen 2 und 3 im Kristiania Gebiet,' Kristiania, 1882.

[6] *Neues Jahrb.* 1882 (2), p. 205.

[7] *Amer. Journ. Sci.* xxi. (1881), p. 21.

Summary of Facts.—The foregoing examples of the alteration superinduced upon stratified rocks in proximity to granite or other eruptive masses might be largely increased; but they may suffice to establish the following deductions in regard to contact-metamorphism.

1. Groups of ordinary sedimentary strata, likewise eruptive rocks associated with them, where they have been pierced by granite or other plutonic rock, have undergone an internal change, whereby their usual lithological characters have been partially or wholly obliterated. This alteration, however, is not always observable at the contact of intrusive masses, and we do not yet know the precise conditions that have determined its development.

2. The distance to which the change extends varies within wide limits, being in some cases scarcely traceable for more than a few feet, in others continuing for two miles or more. The subterranean surface of the plutonic rock, however, being unknown, may frequently lie nearer the surface of the ground than might be supposed. Detached minor areas of

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[1] Stecher, "Contact-Erscheinungen an Schottischen Diabasen," *Tschermak's Mittheil.* ix. 1887, pp. 145-205.

metamorphism may thus be connected with eruptive bosses which have not yet been laid bare by denudation.

3. As the alteration increases in intensity with greater proximity to the plutonic rock, it must be regarded as a result of the protrusion of that rock. But there occur exceptional areas or bands which have undergone a minor degree of change even in the midst of highly altered portions.

4. The character of the metamorphism depends fundamentally upon the nature and mass of the invading rock and on the composition and texture of the materials which have been affected. Sandstones have been changed into quartzite; siliceous schists into hornstone, Lydian-stone, &c.; clay-slates into spotted schists, chiastolite-schists, mica-schists, &c.; argillaceous greywacke and greywacke-slate into "knotenschiefer," mica-slate, and gneiss; limestone into garnet, hornblende, and other minerals. Alternations of distinct kinds of sedimentary strata, such as slate and sandstone, are represented by distinct alternating metamorphic bands, such as quartzite and mica-schist.

5. In some cases, the transformation of a thoroughly clastic rock (clay-slate, greywacke, greywacke-slate, or flagstone) into a completely crystalline one (andalusite-schist, mica-schist, gneiss) has been effected with little or no alteration of the ultimate chemical composition of the mass. In other cases a perceptible alteration in the proportions of the chemical ingredients is traceable.[1] The development of a crystalline structure can be followed through intermediate stages from ordinary sedimentary rock to thoroughly crystalline schist, remains of fossils being still observable after considerable progress has been made towards the completion of a crystalline rearrangement.

6. Not only does the crystalline character increase towards the limit of contact with the eruptive rock, but it is not infrequently accompanied with a progressive development of foliation, the minerals, more especially the mica, crystallizing in folia parallel either with the original stratification of the clastic mass or with cleavage surfaces, should these be its dominant divisional planes.[2] Along the line of contact with granite, the foliation is sometimes excessively crumpled or puckered.

7. The phenomena of alteration observed round intrusive masses of such rocks as diabase and basalt undoubtedly point to the heat of the eruptive rock as their prime cause. Those that occur round the deeper-seated bosses of granitic rocks have probably involved other influences than mere heat; they so closely resemble those of regional metamorphism as to suggest modifications of one common cause for them both. In any case, mere dry heat would probably have been ineffective for the

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[1] This is specially noticeable in the proportion of silica, which is sometimes found to be largely increased in the altered zone, either by an absolute addition of this acid, or by solution and removal of some of the bases. See Kayser, *Z. Deutsch. Geol. Ges.* xxii. p. 153. The development also of such minerals as tourmaline suggests that boric and other acids have been introduced into the rocks.

[2] In the south of Scotland the foliation round the granite bosses is coincident with stratification; round Skiddaw, with cleavage.

production of the more marked phases of the contact-metamorphism round granite. It was accompanied by the co-operation of water, either already present interstitially in the sedimentary rocks, or supplied to them from the eruptive mass, possibly combined with various mineralizing agents and acting under considerable pressure. Moreover, the intrusion of large bosses of eruptive rock not improbably gave rise to mechanical movements in the surrounding parts of the crust, and thereby stimulated crystalline re-arrangements, such as have undoubtedly been generated by crushing, plication, and other movements in areas of regional metamorphism.

§ ii. Regional (Normal) Metamorphism,—the Crystalline Schists.

From the phenomena of metamorphism round a central boss of eruptive rock, we now pass to the consideration of cases where the metamorphism has affected wide areas without visible relation to eruptive matter. It is clear that only those examples are here admissible in evidence where there is distinct proof that what are called metamorphic rocks either pass into masses which have not been metamorphosed, or present characters which are elsewhere proved to have been produced by the alteration either of stratified or of massive rocks.

In the study of this difficult but profoundly interesting geological problem, it is desirable to begin with the examination of rocks in which only the slightest traces of alteration are discernible, and to follow the gradually increasing metamorphism, until we arrive at the most perfectly developed crystalline schists. It is the earliest stages which are of most importance, for it is there that the nature and proofs of the changes can best be established. As already remarked (p. 597), the igneous rocks, from the definiteness of their original structure and composition, offer special facilities for following the nature and extent of the changes involved in the metamorphism of a region or a large series of rocks.

The extent and character of the metamorphism depend in the first place upon the original constitution of the rock, and in the second place upon the energy of the metamorphic agents. Certain rocks resist alteration. Pure siliceous sandstones, for example, become quartzites, but advance no further, though occasionally, under intense strain, their particles are drawn out into a somewhat schistose arrangement. But where felspathic elements are present, particularly where they are the chief constituents, some form of mica almost invariably appears, while new minerals and structures may be developed in progressively increasing abundance, till the rock assumes the character of a true crystalline schist.

Possessing characters which link them on the one hand, with stratified, on the other, with eruptive rocks, the Crystalline Schists present a peculiar type of structure with which are connected some of the most perplexing problems of geology. These rocks cover extensive areas of the surface of the continents, occurring usually wherever the oldest formations have been brought to light. But they everywhere pass under younger formations, so that their visible superficies is probably but a very small part of their total extent. In the northern regions of Europe and of North America, they spread over thousands of square miles, forming the tableland of Scandinavia, the Highlands of Scotland, and a great part of Eastern Canada and Labrador. They likewise commonly rise to the surface along the axes of great mountain-chains in all quarters of the globe. So persistent are they, that the belief has arisen that they everywhere underlie the stratified formations as a general foundation or platform. Some details of their structure will be given in the description of Pre-Cambrian Rocks in Book VI.

The most distinctive character of the schists is undoubtedly their foliation (pp. 103, 175). They have usually a more or less conspicuous crystalline structure, though occasionally this is associated with traces, and even very prominent manifestations, of clastic ingredients (pp. 181, 627). Their foliated or schistose structure varies from the massive type of the coarsest gneiss down to the extremely delicate arrangement of the finest talcose or micaceous schist. They occur sometimes in monotonous uniformity: one rock, such as gneiss or mica-schist, covering vast areas. In other places, they consist of rapid alternations of various foliated masses —gneiss, mica-schist, clay-slate, actinolite-schist, and many other species and varieties. Lenticular seams of crystalline limestone or marble and dolomite, usually with some of the minerals mentioned on p. 151, sometimes strongly graphitic, not unfrequently occur among them, especially where they contain bands of serpentine or other magnesian silicates. Thick irregular zones of magnetite, hæmatite, and aggregates of hornblendic, pyroxenic, or chrysolitic minerals likewise make their appearance.

Another characteristic of the schists is their usual intense crumpling and plication. The thin folia of their different component minerals are intricately and minutely puckered (Figs. 36, 37). Thicker bands may be traced in violent plication along the face of exposed crags. So intense indeed have been the internal movements of these masses, that the geologist experiences great and often insurmountable difficulties in trying to make out their order of succession and their thickness, more especially as he cannot rely on the banding of the rocks as always or even generally an indication of consecutive deposition. Such evidence of disturbance, though usually strongly marked, is not everywhere equally so. Some areas have been more intensely crumpled and plicated, and where this is the case the rocks usually present their most conspicuously crystalline structure.

A further eminently characteristic feature of the schists is their common association with bosses and veins or bed-like sheets of granite, syenite, quartz-porphyry, diorite, gabbro, or other massive rocks. In some regions, indeed, so abundant are the granitic masses and so coarsely crystalline or granitoid are the schists, that it becomes impossible to draw satisfactory boundary-lines between the two kinds of rock, and the conviction arises that in some cases they represent different conditions of the same original material, while in others the result is due to granitization (p. 604).

The question of the formation and geological age of the crystalline schists has given rise to much controversy. Some geologists have maintained that these rocks are to be regarded as portions of the early crust of the globe which consolidated from a molten condition. Others have regarded them as original chemical deposits on the floor of a primeval ocean. These writers, justly repudiating the exaggerated views of those who have sought by metamorphic (metasomatic) processes to derive the most utterly different rocks from each other (for example, limestone from gneiss and granite, granite and gneiss from limestone, talc from granite, &c.), have insisted that the crystalline schists, in common with many pyroxenic and hornblendic rocks (diabases, gabbros, diorites, &c.), as well as masses in which serpentine, talc, chlorite, and epidote are prevailing minerals, have been deposited "for the most part as chemically-formed sediments or precipitates, and that the subsequent changes have been simply molecular, or at most confined in certain cases to reactions between the mingled elements of the sediments, with the elimination of water and carbonic acid." To support this view, it is necessary to suppose that the rocks in question were formed during a period of the earth's history when the ocean had a considerably different relative proportion of mineral substances dissolved in its (then probably much warmer) waters; they are consequently assigned to a very early geological period, anterior indeed to what are usually termed the Palæozoic ages. It becomes further needful to discredit the belief that any gneiss or schist can belong to one of the later stages of the geological record, except doubtfully and merely locally. The more thorough-going advocates of the pristine, "azoic," or "eozoic," date, of the so-called "Metamorphic" or crystalline schists, do not hesitate to take this step, and endeavour, by ingenious explanations, to show that the majority of geologists (as in the case of the Alps, afterwards referred to) have mistaken the geological structure of the districts where these rocks have been supposed to be metamorphosed equivalents of what elsewhere are Palæozoic, Secondary, or Tertiary strata.[1] Some of them even go so far as to assert that, by mere mineral characters, the crystalline rocks of contemporaneous periods can be identified all over the world. They assume that in the supposed chemical precipitation, the same general order has been followed everywhere over the floor of the ocean. Consequently a few hand-specimens of the crystalline rocks of a country are enough in their eyes to determine the geological position of these formations. Other geologists, recognising that the more crystalline members of the series of schists graduate into rocks that are much less crystalline, and even into what are recognisably of sedimentary origin, likewise that they include and pass into masses that were certainly eruptive, have come to regard the schists as a metamorphic series of sedimentary and igneous rocks owing their characteristic foliated structure to some subsequent action upon them.

One of the chief causes of difficulty in discussing the history of these rocks has lain in the fact that the crystalline schists are, in the majority of cases, separated from all other geological formations by an abrupt hiatus.[2]

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[1] See Sterry Hunt's 'Chemical Essays,' p. 382 *seq.*

[2] Many continental geologists, however, believe that the foliation of the schists is usually

Instead of passing into these formations, they are commonly covered unconformably by them, and have usually been enormously denuded before the deposition of the oldest overlying rocks. Hence, not only is there generally a want of continuity between the schists and younger formations, but the contrast between them, in regard to lithological characters and geotectonic structure, is often so exceedingly striking as naturally to suggest the idea that the schists must belong to a far earlier period than that of the oldest sedimentary formations of the ordinary type, and to a totally different order of physical conditions. Natural, however, as this conclusion may be, those who adopt it probably seldom realise to what an extent it rests upon mere assumption. Starting with the supposition that the crystalline schists are the result of geological operations that preceded the times when ordinary sedimentation began, it assumes that they belong to one great early geological period. Yet all that can logically be asserted as to the age of these rocks is that they must be older than the oldest formations which overlie them. If in one region of the globe they appear from under Cretaceous, in another below Carboniferous, in a third below Silurian strata, their chronology is not more accurately definable from this relation than by saying they are respectively pre-Cretaceous, pre-Carboniferous, and pre-Silurian. They may all of course belong to the same period; but where they occur in detached and distant areas, there is as yet no method whereby their synchronism can be proved. To assert it is an assumption which, though in many cases irresistible, ought not to be received with the confidence of an established truth in geology.

In the investigation of the problem of the crystalline schists, much assistance may be derived from a study of the localities where a crystalline and foliated structure has been superinduced upon ordinary sedimentary and eruptive rocks—where, in fact, these rocks have actually been changed into schists, and where the gradation between their unaltered and their altered condition can be clearly traced. In recent years so much attention has been given to these transformations that our knowledge of metamorphic processes has been greatly extended, and the problem of regional metamorphism, though by no means entirely solved, is at least much more clearly understood than it has ever been before.

There is now a general agreement among geologists that a fundamental condition for the production of extensive mineralogical alteration of rocks has been disturbance of the terrestrial crust, involving the intense compression, crushing, fracturing, and stretching of masses of rock. Compression, as we have seen, may give rise to slaty cleavage (p. 312). But the same kind of force has resulted in a further change, wherein chemical reactions have been set up and new minerals have been formed. The effects of pressure and of movement under great strain in quickening chemical activity are now clearly recognised. Not only have the original minerals been driven to re-arrange themselves with their long axes perpendicular to the direction of the pressure, but secondary minerals with well-marked cleavage have been developed along the same lines and

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parallel to the stratification of the immediately overlying sedimentary formations. See, for instance, the summary given by M. Michel Lévy, *Bull. Soc. Géol. France*, xvi. 1888, p. 102.

thus a distinct foliated structure has been induced in what were originally amorphous rocks.

Still more marked are the transformations where the rocks have not merely been compressed, but where they have been crushed, fractured, or stretched. The extraordinary manner in which the crust of the earth has been fractured in some areas of regional metamorphism has been worked out in great detail by the Geological Survey in the north-west of Scotland.[1] We there perceive how slice after slice of solid rock has been pushed forward one over the other, how those accumulated slices have been driven over others of similar kind, how this structure has been repeated again and again, not only on a great scale involving mountain-masses in the movement, but even on so minute a scale that the ruptures and puckerings cannot be seen without a microscope (p. 624).

Such dynamical movements could not but be accompanied with widespread and very marked chemical change. Along the margins of faults or planes of shearing, where the rocks have been ground against each other, there is a selvage of foliated material which with its new mineral combinations gradually passes into the amorphous rock on either side. In such places sericite, biotite, chlorite, or some other secondary product with its cleavage planes ranged in one common direction, shows the line of movement and the reality of the chemical re-combinations. In the body of a mass of rock, also, subject to great strain, relief has been obtained by crushing along certain planes, with a consequent greater development of the secondary minerals along these planes, and the production of a banded or schistose structure in a rock that may have been originally quite homogeneous.[2]

The recognition of the powerful part taken by mechanical deformation in producing the characteristic structures of many schistose rocks has not unnaturally led to some exaggeration on the part of geologists, who were thus provided with what appeared to be a solution of difficulties which at one time seemed insuperable. There can hardly be any doubt that the theory of mechanical deformation has been too freely used and has been applied to structures to which it cannot properly be assigned. Among the coarser gneisses, for example, the segregation of the component minerals in more or less parallel lenticular bands is a structure that seems to find its nearest analogy rather among the segregation-veins of eruptive bosses and sheets than among sheared, cleaved, and foliated rocks, such as undoubtedly have been the originals of many schists. There is nothing to show that this parallel banding is not an arrangement of the materials of an igneous magma before final consolidation.

But while this tendency to a too liberal use of dynamical causes in explication of all the structures of the crystalline schists must be admitted, we are now furnished with ample evidence of the efficacy of mechanical movements in the production of regional metamorphism. It is frequently possible to detect portions of the original structures, to show that they belonged to certain familiar and definite types of sedimentary or eruptive rocks, and to trace every stage of transition from them into the most perfectly developed crystalline schist. In the crushing down of large masses of rock during powerful terrestrial movements, lenticular cores of the rocks have frequently escaped entire destruction. Round these cores the pulverised material of the rest of the rock has been made to flow, somewhat like the flow-structure round the porphyritic crystals of a cooling lava. And successive gradations may be followed until the cores, becoming smaller by degrees, pass finally into the general reconstructed material. That this structure is not original, but has been superinduced upon the rocks after their solidification can be abundantly demonstrated. Among the sedimentary formations the elongation and flattening of the pebbles in conglomerates, and the transition from grits or greywackes into foliated masses, prove the structure to have been superinduced. Among eruptive rocks the crushing down of the original minerals, and their transformation into others characteristic of foliated rocks, afford the same kind of proof.[1]

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[1] *Quart. Journ. Geol. Soc.* xliv. (1888) p. 378.

[2] G. H. Williams, *Bull. U.S. Geol. Surv.* No. 62 (1890), pp. 202-207.

So great has been the pressure exerted by gigantic earth-movements upon the rocks of the crust that even the most solid and massive materials have been sheared, and their component minerals have been made to move upon each other, giving a flow-structure like that artificially produced in metals and other solid bodies (*ante*, p. 316). But it may be doubted whether this motion is ever strictly molecular without rupture of the constituent minerals. Microscopic examination shows that, at least as a general rule, the minerals in the most thoroughly bent and crushed rocks have been broken down. It is observable that under the effects of mechanical strain the minerals first undergo lamellation, twinning being developed along certain planes. This structure increases in distinctness with the intensity of the strain so long as the mineral (such as felspar) retains its cohesion, but the limit of endurance is soon reached, beyond which it will crack and separate into fragments, which, if the movement is arrested at this stage, may be cemented together by some secondary mineral filling up the interspaces. But should the pressure increase, the mineral may be so wholly pulverised as to assume a finely granular structure or mosaic of interlocking grains, which under the influence of continual shearing may develop a streaky arrangement, as in flow-structure and foliation.[2]

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[1] On the mechanical deformation and dynamical metamorphism of rocks see A. Heim, "Untersuchungen uber den Mechanismus der Gebirgsbildung," 1878; A. Rothpletz, *Zeitsch. Deutsch. Geol. Gesell.* xxxi. (1879) p. 374; H. Reusch, "Die fossilien-fuhrenden krystallinischen Schiefer von Bergen," German translation by Baldauf, 1883. *Neues Jahrb.* (Beilageband), 1887, p. 56; "Bommeloen og Karmoen," 1888; *Rep. Geol. Congress, London*, 1891, p. 192: Lehmann, "Untersuchungen uber die Entstehung der altkrystallinischen Schiefer," 1884; J. J. H. Teall, *Geol. Mag.* 1886, p. 481; G. H. Williams, *Bull. U.S. Geol. Survey*, No. 62 (1890). For an instance of the metamorphism of a conglomerate into albite schist see J. E. Wolff, *Bull. Mus. Comp. Zool. Harvard*, xvi. No. 10, p. 174 (1891). The Papers on the Crystalline Schists by Heim, Lory, Lehmann, Michel Lévy, Lawson, and the U.S. Geol. Survey in the report of the London Session of the International Geological Congress (published in 1891) should also be consulted.

[2] Lehmann, *op. cit.* pp. 245, 249; G. H. Williams, *Bull. U.S. Geol. Survey*, No. 62, p. 47.

One of the most important effects of this mechanical deformation and trituration under gigantic pressures has been the great stimulus thereby given to chemical reactions. So constant and so great have these reactions been, and so completely in many cases have the ingredients of the rocks been recrystallized in fresh combinations, that the new structures thus produced have masked the proof of the mechanical deformations that preceded or accompanied them. It is in the main to the light thrown on the subject by the microscopical investigation of the minute structures of the metamorphosed masses that we are indebted for the recognition of the important part played by pressure and stretching in the production of the more essential and characteristic features of metamorphic rocks. Many chemical rearrangements may undoubtedly take place apart from any such dynamical stresses, but none of these stresses appear to have affected the metamorphic rocks without being accompanied by chemical and mineralogical readjustments.

The mineral transformations observable in regional metamorphism "may consist (1) in the breaking up of one molecule into two or more with but little replacement of substance, as in the formation of saussurite from labradorite; (2) in a reaction between two contiguous minerals, each supplying a part of the substance necessary to form a new compound of intermediate composition, more stable for the then existing conditions than either, as in the formation of a hornblende zone between crystals of olivine or hypersthene and plagioclase; or (3) in more complicated and less easily understood chemical reactions, like the formation of garnet or mica from materials which have been brought together from a distance, and under circumstances of which it is at present impossible to state anything with certainty."[1] The following transformations especially deserve attention.

Micasization—the production of mica as a secondary mineral from felspars or other original constituents. One of the most common forms of this change is where the silky unctuous *sericite* has been developed from orthoclase (sericitization). The formation of mica is one of the most common results of the mechanical deformation of rocks, and is most conspicuous where the pressure or stretching has been most intense. Massive orthoclase rocks, such as granite, quartz-porphyry or felsite, when most severely crushed, pass into sericite schist; felspathic grits and slates may be similarly changed.[2]

Uralitization—the conversion of pyroxene into compact or fibrous hornblende. This change may not be a mere case of paramorphism or molecular rearrangement, but seems generally to involve a certain amount of chemical rearrangement, such as the surrender of part of the lime of the pyroxene towards the formation of such combinations as epidote,[3] and the higher oxidation of the iron.[4] It has taken place on the most extensive scale among the crystalline schists. Rocks which can be shown to have been originally eruptive, such as diabases, have been converted into epidiorite, and where the deformation has advanced further, into hornblende-schist or actinolite-schist.

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[1] G. H. Williams, *Bull. U.S. Geol. Survey*, No. 62, p. 50. This admirable essay, with its copious bibliography, will well repay the careful perusal of the student. I am indebted to it for the abstract of metamorphic processes above given.

[2] See especially Lehmann's "Untersuchungen uber die Entstehung der altkrystallinischen Schiefergesteine," where the development of sericite as a result of mechanical deformation is well enforced.

[3] Rosenbusch, "Mikrosk. Phys." 2nd edition (1887), p. 185.

[4] J. J. H. Teall, *Quart. Journ. Geol. Soc.* xli. (1885) p. 137.

Epidotization—the production of epidote in a rock from reactions between two or more minerals, especially between pyroxene or hornblende and plagioclase. In some cases diabases have been converted into epidiorites or aggregates of epidote and quartz or calcite.[1]

Saussuritization—the alteration of plagioclase into an aggregate of needles, prisms, or grains (chiefly zoisite), imbedded in a glass-like matrix (albite), by an exchange of silica and alkali for lime, iron, and water. This change has largely affected the felspar of coarse gabbros or euphotides, especially in districts of regional metamorphism.[2]

Albitization—a process in which, while the lime of the plagioclase is removed or crystallizes as calcite, instead of forming a lime-silicate like epidote or zoisite, the rest of the original mineral recrystallizes as a finely granular aggregate or mosaic of clear grains of albite. Examples of this change may be found in association with the development of saussurite.[3]

Chloritization—an alteration in which the pyroxene (or hornblende) of the so-called "greenstones" has been changed into secondary substances (1) more or less fibrous in structure allied to serpentine, not pleochroic but showing a decided action on polarized light; or (2) scaly, pleochroic, polarizing so weakly as to appear isotropic, and more or less resembling chlorite. This alteration is rather the result of weathering than of metamorphism in the strict sense.[4] Where chloritization and epidotization have proceeded simultaneously in aluminous pyroxene or hornblende, the result is an aggregate of sharply defined pale yellow crystals of epidote in a green scaly mass of chlorite.[5]

Serpentinization—an alteration more especially noticeable among the more highly basic igneous rocks in which olivine has been a prominent constituent. The gradual conversion of olivine into serpentine has been already described (p. 75), and the occurrence of massive serpentine has been referred to (p. 173).

Alterations of Titanic Iron.—The ilmenite or titaniferous magnetite of diabases and other eruptive rocks undergoes alteration along its margins and cracks into a dull grey substance (leucoxene, p. 71), which is now known to be a form of titanite or sphene. The grey rim frequently passes into well-defined aggregates and crystals of sphene.[6]

Marmarosis, or the alteration of an ordinary dull limestone into a crystalline-granular marble (p. 602) may be again referred to here as one of the characteristic transformations in regional metamorphism.

Dolomitization. See p. 321.

Granitization. See p. 579.

Production of New Minerals.—In tracts of regional metamorphism a number of secondary minerals may be observed to have crystallized out, and to be characteristic of the schistose rocks. Among the most conspicuous of these are white and black mica, garnet, quartz, epidote. Garnet occurs abundantly as a constituent of mica-schist and gneiss, and has resulted from the alteration of both clastic and massive rocks (compare p. 603).

A few illustrative examples of regional metamorphism, culled from different quarters of the globe, and various geological formations, may here be given. The subject is further discussed in Book VI. Part I.

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[1] A. Schenck, "Die Diabase der oberen Ruhrthals," 1884.

[2] Hagge, "Mikroskopische Untersuchungen uber Gabbro," &c. Kiel, 1871, p. 51.

[3] Lossen, *Jahrb. Preuss. Geol. Landesanst.* 1883, p. 640; 1884, pp. 525-530.

[4] Rosenbusch, "Mikroskopische Physiographie," pp. 180-184.

[5] G. H. Williams, *Bull. U.S. Geol. Surv.* No. 62, p. 56.

[6] A. Cathrein, *Zeitsch. Kryst. und Mineral.* vi. (1882) p. 244.

Early Stages of Metamorphism.—In 1871 Zirkel showed that some of the clay-slates of the disturbed Silurian and Devonian tracts of central Europe contain minute microscopic needle-shaped microlites. Considerable diversity of opinion has arisen as to the nature of these rudimentary crystallizations. They have been regarded as microlites of hornblende, rutile, epidote, &c. More recently they have been carefully isolated, extracted, and analysed by E. Kalkowsky, who regards them as staurolite, constituting from two to five per cent of the rock.[1] The whet-slate of Belgium has been found by Renard to be characterised by the presence of abundant garnets. Microscopic tourmaline and rutile likewise occur among clay-slates. No one would class as metamorphic, the rocks in which these microlites occur, and yet the presence in them of microscopic microlites and crystals shows that they have undergone some of the initiatory stages of metamorphism, by the development of new minerals. All that is known of the probable origin of these minerals, negatives the supposition that they could have been formed in the original sediment of the sea-bottom on which the organisms entombed in the deposits lived and died. For their production, a temperature and a chemical composition of the water would seem to have been required, such as must have been inimical to the co-existence in the same water of such highly organised forms of life as brachiopods and trilobites.

One of the most marked of the early stages of regional metamorphism is characterised by the appearance of fine scales of some micaceous mineral (muscovite, biotite, &c.) As these micaceous constituents increase in number and size, they impart a silky lustrous aspect to the surfaces on which they lie parallel. In many cases, these surfaces are probably those of original deposit, but where rocks have been cleaved or sheared, the mica ranges itself along the planes of cleavage or shearing. The Cambrian tuffs of South Wales, of which the bedding still remains quite distinct, present interesting examples of the development of a mica along the laminæ of deposit.[2] The Dingle beds of Cork and Kerry, on the other hand, have been subjected to cleavage, and the mica appears along the cleavage planes, which have a lustrous surface. The Torridonian and Cambrian sandstones, quartzites and shales of north-west Scotland show a development of mica along the surfaces of the shearing-planes.

Ardennes.—As far back as 1848, Dumont published a description of the Belgian Ardennes, in which he showed that a zone of his "terrains ardennais et rhénan," had undergone a remarkable metamorphism. Sandstones, in approaching this zone, were transformed, he said, into quartzites, and by degrees passed into rocks characterised by the presence of garnet, hornblende, and other minerals; the slates (phyllades) graduated into dark rocks, in which magnetite, titanite, and ottrelite had been developed. Yet the fossiliferous character of the strata thus metamorphosed had not been destroyed. In specimens showing a gradation from a grit to a compact garnetiferous and hornblendic quartzite, Prof. Sandberger, to whom they were submitted, recognised the presence of the two Devonian shells, *Spirifer macropterus* and *Chonetes sarcinulatus.* "The garnets and the fossils are associated in the same specimen," he wrote, adding, "who, after this, can hesitate to admit that the crystalline schists and quartzites of the Hundsruck and Taunus are likewise metamorphosed Taunusian rocks?"[3]

In 1882 M. Renard, fortified with the resources of modern petrography, renewed the examination of Dumont's metamorphic area of the Ardennes, and conclusively established the accuracy of all the main facts noticed by the earlier observer. Not only do the geological structure of this region, and the occurrence of recognisable fossils, show that the rocks, now transformed into more or less crystalline masses, were originally parts of the ordinary series of Devonian sandstones, greywackes, and shales, but the microscope comes in to confirm this conclusion. The original clastic grains of quartz and the diffused carbonaceous material of the unaltered strata can still be recognised in their metamorphosed equivalents. But there have been developed in them abundant new minerals—garnet (1 to 2 mm.), hornblende, mica, titanite, apatite, bastonite, ottrelite.[1]

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[1] *Neues Jahrb.* (1879) p. 382. These bodies are to be distinguished from the minute crystals of such durable minerals as zircon, rutile, &c., so often recognisable as clastic grains in sediments, and which may often have played a part in the sedimentation of more than one geological period.

[2] *Q. J. Geol. Soc.* xxxix. (1883) p. 310.

[3] *Neues Jahrb.* (1861) p. 677.

Dumont appears to have believed that the metamorphism which he had traced so well in the Ardennes was to be attributed to the influence of underlying masses of eruptive rocks, though he frankly admitted that the metamorphism is less marked where eruptive veins have made their appearance than where they have not.[2] M. Renard, however, points out that eruptive rocks are really absent, and that the association of minerals proves that the metamorphosed rocks could not have been softened by a high temperature, as supposed by Dumont, otherwise the simultaneous presence of graphite and silicates, with protoxide iron bases, such as mica, hornblende, &c., would certainly have given rise at least to a partial production of metallic iron. He connects the metamorphism with the mechanical movements which the rocks have undergone along the altered zone.[3] The metamorphism of this region has since been described by Professor Gosselet, who also regards it as due to dynamical causes.[4]

Taunus.—A similar example of regional metamorphism extends into the tracts of the Taunus and Hundsruck. In 1867 K. A. Lossen published an elaborate memoir on the structure of the Taunus, which is now of classic interest in the history of opinion regarding metamorphism.[5] He showed that below the middle Devonian limestone, the usual lower Devonian slates, greywackes, and quartzites rise to the surface, but that these, traced southwards, pass gradually into various crystalline schists. Among these schists, he distinguished sericite-gneiss, mica-schist, phyllite, knotted schist, augite-schist, sericite-lime-phyllite, quartzite, and kiesel-schiefer. As intermediate grades between these crystalline masses and the ordinary clastic strata, he observed quartz-conglomerates, with a crystalline schistose matrix, or with albite crystals, and quartzites with sericite or mica. He concluded that while these crystalline rocks present the most complete analogies with those of the Alps, Silesia, Brazil, &c., they are yet so intimately bound up alike petrographically and stratigraphically with strata containing Devonian fossils, and into which they pass by semi-crystalline varieties, that they must be considered as of Devonian age. Subsequently K. Koch proposed to regard the crystalline schists of the Taunus as Cambrian (Huronian),[6] and they have been indicated on the Geological Survey map as Cambrian or Silurian. But the fact that a conformable

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[1] Renard (*Bull. Mus. Roy. Belgique*, i. (1882) p. 14) estimates the components of one of these altered rocks to be—

Graphite	4·80
Apatite	1·51
Titanite	1·02
Garnet	4·14
Mica	20·85
Hornblende	37·62
Quartz	30·62
Water	1·32
	101·88

[2] Renard, *op. cit.* p. 34.

[3] *Op. cit.* p. 37.

[4] See his great Monograph on the Ardennes, *Mém. Carte Géol. France*, 1888, chap. xxv.

[5] 'Geognostische Beschreibung der linksrheinischen Fortsetzung des Taunus,' &c., *Z. Deutsch. Geol. Ges.* xix. (1867) p. 509, (1885) p. 29.

[6] See Lossen's reply, *Z. Deutsch. Geol. Ges.* xxix. (1877) p. 341. He argues convincingly against the supposition that these can be original chemical deposits of Cambrian age. (See also Renard, *Bull. Mus. Roy. Belg.* i. p. 31, *note.*)

sequence can be traced from undoubted fossiliferous Devonian strata downwards into these crystalline schists makes it immaterial what stratigraphical name may be applied to them. They are almost certainly Devonian, as Lossen described them, and in any case, they are unquestionably the metamorphosed equivalents of what are elsewhere ordinary sedimentary strata.

Scandinavia is mainly composed of crystalline schists which have been assigned to the so-called Archæan system. That some portions of them cannot be of so ancient a date was shown some years ago by Tornebohm in the uplands of Sweden. More recently similar deductions have been drawn from a study of the development of the rocks in Norway. At the Hardanger Fjord the following order of succession was established in 1875 and 1877 by W. C. Brogger:[1]—

Crystalline schists (diorite-schists, hornblende-schists, garnetiferous mica-schists, true gneisses, &c.), the whole series becoming more and more crystalline towards the higher beds.	
Greenish micaceous schists (phyllites). This and the overlying group must be several thousand feet thick.	
Impure white marble (probably orthoceratite limestone) . . .	30 ft.
Blue quartz-sandstone	100 ,,
Black, little altered alum-schist, with *Dictyograptus* band . . .	150 ,,

This section confirmed the early conclusion of Naumann that the great series of crystalline schists of the Norwegian uplands overlies the Silurian stage 2 in the Christiania district. Subsequently H. H. Reusch obtained from the Bergen district clear proof of the Silurian age of certain crystalline rocks in that part of Norway.[2] He found among masses of mica-schist, hornblende-schist, gneiss, and other crystalline rocks, intercalated bands of conglomerate which, while obviously of clastic origin, have undergone enormous compression, the pebbles being squeezed flat and the paste having become more or less crystalline. The occurrence of such bands suggests a sedimentary origin for the whole series of deposits. But from several localities he obtained fossils which have been recognised as undoubtedly Upper Silurian. Some of the fossils occur in a crystalline limestone, which is intercalated in a dark lustrous phyllite. But they are found, as casts, most abundantly in a light-grey lustrous micaceous schist, which, under the microscope, is observed to be composed in large measure of quartz, not having a fragmental aspect, with mica, rutile, and tourmaline. The fossils recognised comprise *Phacops, Calymene,* several undeterminable gasteropods and brachiopods, *Cyathophyllum, Halysites catenularia, Favosites, Rastrites, Monograptus,* and some others.

According to Reusch the sequence of rocks is continuous, and their thickness must be at least 16,000 feet. If we suppose that the fossiliferous zones have been brought into an older series by plication of the crust, the fact remains that the rock in which most of the fossils occur is itself a micaceous schist, like those among which it is imbedded, and therefore a metamorphic rock. It is consequently proved that some at least of the metamorphic rocks of Norway are of Silurian age, and are associated with evidence of great mechanical movements in the crust of the earth.

The Alps.—In the geological structure of the central Alps, crystalline schists play an important part. Originally these rocks were regarded as one series, of much more ancient date than the ordinary sedimentary formations, and of very different origin. The discovery of Silurian, Devonian, Carboniferous, and Jurassic fossils in various schists and altered limestones surrounding the central gneiss, led to the belief that these are metamorphosed sedimentary rocks of Palæozoic, Mesozoic, and even of older Tertiary date. This belief has subsequently been attacked by several able observers, who, starting with the assumption that the crystalline schists must be everywhere of great relative antiquity, have endeavoured to show that the fossiliferous bands intercalated among them have been brought into this position by plication, and that there is no evidence that any part of the schists is even of Palæozoic age.[1] Now it must be admitted that in the sections, even as drawn by those who adopt this explanation, the obvious and natural interpretation is that which has been so generally adopted—that the fossiliferous beds are actually part of the crystalline series in which they are imbedded. If the apparent order is deceptive, this must be proved by those who maintain it. If, however, we turn to their writings we find a good deal of strong assertion, and various more or less ingenious attempts to construct sections in which the abnormal position of the fossiliferous beds is to be accounted for. It does not appear to be realised that on the supposition of the high antiquity and original discordant infraposition of the schists, the chances are small that, in any plication of the mountains, the unconformable fossiliferous strata would become conformably stratified with ancient schists even at one locality. But when we look at the published sections of the Alps, and find that the parallelism between the schists and the enclosed fossiliferous bands occurs again and again at widely separated localities, and that in fact this is their normal position, it becomes utterly incredible that the conformability can be the result of plication, except on the supposition that the foliation of the schists is not their original structure, but a new one superinduced upon them at the time of the plication and metamorphism of the fossiliferous strata.[2]

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[1] 'Die Silurischen Etagen 2 und 3 im Kristiania Gebiet,' p. 352. The Swedish work of Tornebohm is referred to *postea,* p. 711.

[2] 'Silurfossiler og Pressede Konglomerater i Bergensskifrene,' Christiania, 1882; or the same work translated into German by R. Baldauf, 'Die fossilien-fuhrenden krystallinischen Schiefer von Bergen in Norwegen,' Leipzig, 1883. In the year 1889 I had an opportunity of personally going over Dr. Reusch's Bergen region and of collecting fossils from the rocks in which he found them. There can be no doubt that he has demonstrated that the metamorphism of that district has been connected with powerful dynamical movements, the latest of which are of younger date than the Upper Silurian period.

Let us, however, grant, for the sake of argument, that the concordance is everywhere deceptive, and that between the schists and the fossiliferous series of formations there is really a great hiatus.[3] When the fossil-bearing intercalations are examined they are themselves found to be metamorphosed. The Jurassic limestones have been marmarized, and the shales have become lustrous sericite-schists in which belemnites and other fossils are recognisable. The Triassic rocks have been in like manner rendered crystalline, and present Secondary crystals of albite, quartz, mica, tourmaline, garnet, &c. The Carboniferous strata, when their age can be determined by enclosed fossils, consist of dark anthracitic bands, which have undergone less alteration than the adjacent schists.[4]

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[1] Consult Lory, 'Description géologique du Dauphiné' (1860), part i. §§ 40-42; *Compte rendu Congrès Géologique International*, Paris, 1881, pp. 39-43; *Bull. Soc. Géol. France*, 3e série, ix. (1881) pp. 652-679; Favre, 'Recherches géologiques dans les parties de la Savoie, &c., voisines du Mt. Blanc' (1867), chaps. xxi. xxiv. xxv.; A. Muller, *Mém. Soc. d'Hist. Nat. Bâle*, 1865-70. See also Sismonda, *Real. Acad. Sci. Torin.* (2) xxiv. (1866) p. 333; Sterry Hunt, 'Chem. Essays,' pp. 283, 328. Bonney, Address, *Quart. Journ. Geol. Soc.* xlii. (1886) p. 38; xlvi. (1890) p. 187, and other papers cited, *postea*, p. 624.

[2] See this structure illustrated by that of north-west Scotland, *postea*, p. 624.

[3] Professor Lory believed that in the Western Alps there is a conformability and even gradation between the true crystalline schists and the Palæozoic and Secondary rocks. He regarded the crystalline character of the latter as an original feature dating from the time of deposition. See his *résumé* in the Report of the London meeting (1888) of the International Geological Congress, and the views of M. Michel Lévy in the same Report.

[4] It is well known that carbonaceous strata can be recognised across zones of contact-metamorphism, when the normal characters of the ordinary strata above and below them have been destroyed. This is well seen in the case of the black graptolitic shales of the south of Scotland, and, still more strikingly, in those of Christiania. See Brögger's memoir cited on p. 621.

But the extraordinary way in which many of the plants in the Alpine Carboniferous rocks have been distorted indicates the enormous shearing which these rocks have undergone.[1] At Vernayaz, near Martigny, the Carboniferous strata can hardly be separated from the schists;[2] and, indeed, had Carboniferous plants not been found in them the idea would probably never have occurred to any one to draw a line between them. At the well-known locality of Petit Cœur, the plants so abundantly and admirably preserved in black schist, have had their original substance replaced by a white hydrous mica.[3]

A detailed investigation of the geotectonic and petrographical relations of these intercalated Carboniferous bands was carried out in 1882 by the late Mr. Stur, Director of the Austro-Hungarian Geological Survey, and Baron von Foullon.[4] On the northern border of the Styrian Alps near Leoben a group of crystalline schists 10,000 to 13,000 feet thick reclines steeply (but it is said conformably) against gneiss. It consists of phyllite-gneiss, mica-schist, and chlorite-schist, with four bands of dark graphitic schist and one or two seams of limestone. The plant-bearing graphitic schist is full of plant-remains (*Calamites ramosus*, *Pecopteris lonchitica*, *Lepidodendron phlegmaria*, &c.) The association of plants and the occurrence of bands of graphite, representative doubtless of former beds of coal, indicate that these carbonaceous rocks belong to the well-known Schatzler group of the lower Coal-series of Silesia. The whole succession of schists of which these plant-bearing beds are members, forms one continuous group, which Stur recognised as traceable for a long distance on the northern margin of the central range of the north-eastern Alps. He insisted that this group of schists cannot be the result of original chemical deposition, but, on the contrary, that it is shown, by a great series of facts, to be the metamorphosed equivalent of what, elsewhere, are unaltered Carboniferous strata. The distortion of the fossils, which proves that the rocks have behaved like plastic masses under the strain of mountain-making, the alteration of their substance into anthracite or graphite, and its replacement by micaceous silicates, are evidence of a serious metamorphism. On the other hand, the occurrence of unaltered plant-bearing Carboniferous rocks elsewhere in the Alps shows that, as usual, the metamorphism has not been everywhere equally intense. Stur concluded that there was every encouragement to search for fossils in the schist envelope of the central Alpine gneiss.[5]

Baron von Foullon describes the petrographical characters of the various members of the group of schists in which the plants occur near Leoben. As to the thoroughly crystalline character of the phyllite-gneiss, mica-schist, &c., there can be no dispute. It will be enough here to refer briefly to the constitution of the graphite-schist in which the plants occur. Hand-specimens present a dull fracture, on which none of the components, except the graphite, can be recognised, though sometimes they show a greenish fibrous asbestiform mineral. In thin slices, the rock is seen to be composed of quartz grains, chloritoid, an asbestos-like substance, and a mica, with abundant "clay-slate microlites," and diffused carbonaceous matter. It resembles the mica-chloritoid-schists of the Taunus. Some of the chloritoid-schists or quartz-phyllites associated with this plant-bearing band are also graphitic. Petrographical investigation thus concurs with the stratigraphical evidence to prove that a tract of the crystalline schists of the north-eastern Alps consists of metamorphosed Carboniferous rocks.

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[1] See Heer's 'Flora Fossilis Helvetiæ' (Steinkohlen Flora), plate iv. fig. 1; v. figs. 1, 3, viii. figs. 1, 2; xiii. fig. 1, &c.

[2] Favre, 'Recherches géol.' ii. p. 351. The same fact is admitted by Lory to be often true elsewhere (*Bull. Soc. Géol. France*, ix. (1881) p. 653).

[3] Favre, *op. cit.* iii. p. 192.

[4] *Jahrb. Geol. Reichsanst.* xxxiii. (1883) pp. 189, 207. See also Toula, *Verh. Geol. Reichsanst.* 1877, p. 240.

[5] He had, many years before this, announced his belief that the schistose envelope (Schieferhulle) of the Alps probably represents Palæozoic rocks. Stache, in 1874, wrote that "the question now is how far Cambrian or Silurian rocks are represented." *Jahrb. Geol. Reichs.* 1874, p. 159. In 1884 he thought that the epicrystalline condition of the Silurian rocks in the Alps might be due to original crystalline precipitation: *Z. Deutsch. Geol. Ges.* 1884, p. 356.

The Silurian rocks, which in the eastern Alps are greywacke and slate, become more and more crystalline as they are followed westwards. The Liassic shales become micasized towards the central mountains, the fossils by degrees disappear, and the limestones assuming a jointed aspect, finally pass into a completely crystalline condition. In the Vaud Alps, the belemnites of the middle Oxfordian shales gradually disappear in proportion as the rock becomes more schistose, till at the Diablerets it is an almost crystalline sericitic schist.[1] The Eocene strata, also, under intense compression, have assumed the character of slates, which are worked for economic purposes.[2]

So far, therefore, from being entirely a pre-Cambrian series, the crystalline schists of the Alps can be demonstrated to include metamorphosed Palæozoic and Secondary rocks along their outer border. How far towards the central mass of the mountains they are of Palæozoic age has yet to be determined. As the rocks become more and more crystalline in that direction it may not always be possible to define the base of the altered Palæozoic rocks. That there is a nucleus of ancient or "Archæan" gneisses is not disputed; but its limits must be proved by stratigraphical evidence.[3]

Scottish Highlands.—This region consists mainly of crystalline schists with bosses of granite, porphyry, &c., which, stretching through four degrees of latitude and four and a half of longitude, must cover an area of not less than 16,000 square miles at the surface. As, however, they sink beneath later formations, and are prolonged into Ireland, their total area must be still more extensive. The oldest rocks consist mainly of a remarkably coarse crystalline gneiss (Lewisian, 1 in Fig. 311), with abundant pegmatite veins, seen in Sutherland and Ross, the two north-westerly counties of Scotland. This gneiss, which will be described in the section on pre-Cambrian rocks in Book VI., is unconformably overlain by nearly flat brownish-red (Torridonian) sandstones, conglomerates and breccias (2), which in turn are surmounted unconformably by inclined beds of quartzite (3, 4), shales (5), calcareous grit (6), and limestones (7), the geological age of which is fixed by the occurrence of recognisable fossils in them. The quartzite is full of annelide-burrows; the shales contain *Olenellus*—the distinctive trilobite of the lowest Cambrian rocks; the limestone has yielded *Maclurea*, *Murchisonia*, *Ophileta*, *Pleurotomaria*, *Orthis*, *Orthoceras*, *Piloceras*, and many more forms, indicating Cambrian and possibly the very lowest Silurian horizons. The strata are generally crowded with carbonaceous worm-casts (the so-called "fucoids"). Along their western margin, these rocks are so little altered that they do not in any way deserve the name of metamorphic. Eastwards, however, they pass under various schists and gneisses (8, 9, 10), which form a vast overlying, thoroughly crystalline series. It was believed by Macculloch and Hay Cunningham that the fossiliferous beds truly underlie, and are older than, the eastern gneiss. This view was adopted and worked out in some detail by Murchison, who extended his generalisation over the whole area of the Highlands, which he regarded as composed essentially of metamorphosed Silurian rocks (see p. 698). Other geologists supported Murchison, whose opinions met with general acceptance. Nicol, however, contended that the overlying or "newer gneiss" is merely the old gneiss brought up by faulting. Later writers, particularly Prof. Lapworth, Dr. Callaway, and Dr. Hicks, advanced somewhat similar opinions; but the difficulty remained of explaining how, if the "newer gneiss" is really older than the fossiliferous strata, it should overlie them so conformably as to have deceived so many observers. The problem was subsequently attacked independently by Prof. Lapworth and by the Geological Survey, especially by Messrs. B. N. Peach, J. Horne, W. Gunn, C. T. Clough, L. Hinxman, and H. M. Cadell, and I believe it has now been solved. I fully shared Murchison's belief in a continuous upward succession from the fossiliferous Lower Silurian strata into the overlying schists, but the subsequent detailed investigation of the ground convinced me that this belief could no longer be entertained.

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[1] Renevier, *Bull. Soc. Géol. France* (3), ix. p. 650; xvii. (1889) p. 884.

[2] Lory, *Bull. Soc. Géol. France*, ix. (1881) p. 651.

[3] M. Vacek has shown an unconformability between the older central schists and the Silurian gneiss, diorite-schist, mica-schist, and chloritoid-schist. *Jahrb. Geol. Reichsanst.* xxxiv. (1884) p. 620. The Palæozoic and Secondary age of part of the schists of the Alps is enforced by Heim, 'Mechanismus der Gebirgsbildung,' 1878; *Compte rend. Congres Géol. International London* (1888), p. 16; *Nature*, xxxviii. (1888) p. 524; *Quart. Journ. Geol. Soc.* xlvi. (1890) p. 236. Grubenmann, *Mittheil. Thurganischen Naturf. Gesellsch.* Heft viii. (1888). Baltzer, 'Beitrage zur Geol. Karte der Schweiz,' No. 24 (1888). The volumes of these "Beitrage" contain ample details regarding the geological structure of the Alps. P. Termier, *Comptes rend. Acad. France*, cxii. (1891) p. 900. Prof. Bonney holds that the crystalline schists of the Alps are older than the Palæozoic rocks. See, for example, his Address to the Geol. Soc. (*Q. J. Geol. Soc.* vol. xlii. 1886, p. 66), and the same Journal for 1889, p. 67; 1890, p. 187; 1892, p. 390.

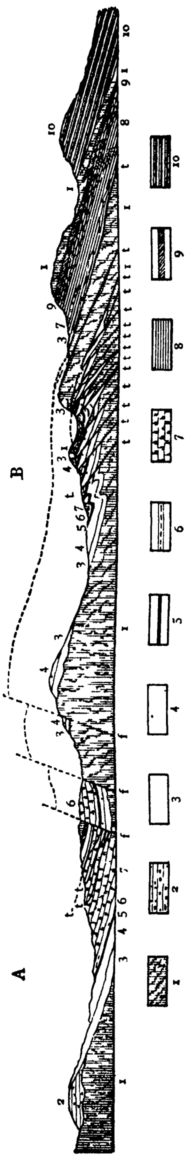

Fig. 311.—Diagram-section to show the geological structure of the North-West of Scotland.

10. Gneissose Flagstones, &c. } NEWER OR EASTERN GNEISS ("MOINE SCHISTS.")
9. Siliceous schist . . . .
8. { Frilled schist . . . . / Green schist . . . .
7. Durness-Eriboll Limestone } CAMBRIAN OR LOWER SILURIAN.
6. Serpulite Grit (*Salterella*) .
5. Fucoid-Beds (*Olenellus*) . . } CAMBRIAN
4. Piped Quartzite (*Annelides*)
3. { False-bedded Quartzite . / Basal Breccia . . . .
2. Red Sandstones and Conglomerates . . } TORRIDON SANDSTONE.
1. Gneiss, Granite, Pegmatite, &c. . . . } LEWISIAN GNEISS.

A, Durness Area; B, Eriboll Area; f f, Normal Faults; t t, Reversed Faults and Thrust-planes; Dotted lines, continuation of normal Faults and thrust-planes.

Tracing the unaltered Cambrian strata eastwards from where they lie in their normal position upon the Torridon sandstone and old gneiss below, we find them begin to undergo curvature. They are thrown into N.N.E. and S.S.W. anticlinal and synclinal folds which become increasingly steeper on their western fronts until they are disrupted, and the eastern limb of a fold is pushed over the western. By a system of reversed faults (t t in Fig. 311), a single group of strata is made to cover a great breadth of ground and actually to overlie higher members of the same series. The most extraordinary dislocations, however, are the Thrust-planes. These have so low a hade that the rocks on their upthrow side have been, as it were, pushed horizontally westwards, in some places for a distance of at least ten miles. But for the evidence of the clear coast-sections, these thrust-planes could hardly be distinguished from ordinary stratification-planes, like which they have been plicated, faulted and denuded (dotted lines in Fig. 311). Here and there an outlier of horizontally displaced Lewisian gneiss may be seen capping a hill of quartzite and limestone like an ordinary overlying formation.

The general trend of all the foldings and ruptures is N.N.E. and S.S.W., and as the steeper fronts of the folds face the west, the direction of movement has obviously been from the opposite quarter. That there has been an enormous thrust from the eastwards, is further shown by a series of remarkable internal re-arrangements that have been superinduced upon the rocks. Every mass of rock, irrespective of lithological character and structure, is traversed by striated surfaces, which lie approximately parallel with those of the thrust-planes, and are covered with a fine parallel lineation running in a W.N.W. and E.S.E. direction. Along many zones near the thrust-planes, and for a long way above them, the most perfect shear-structure has been developed (Fig. 256). The coarse pegmatites in the gneiss have had their pink felspar and milky quartz crushed and drawn out into fine parallel laminæ, till they assume the aspect of a rhyolite in which fluxion-structure has been exceptionally well developed. Hornblende-rock passes into hornblende-schist. Sandstones, quartzites, and shales become finely micaceous schists. The annelide-tubes in the quartzite are flattened and drawn out into ribbands. New minerals, especially mica, have been abundantly developed along the superinduced divisional planes, and, in many cases, their longer axes are ranged in the same dominant direction from E.S.E. to W.N.W.

The whole of these rocks have undergone such intense shearing during their westward displacement that their original characters have in many cases been obliterated. Among them, however, can be recognised bands of gneiss which undoubtedly belong to the underlying Lewisian series. With these are intercalated lenticular strips of Cambrian quartzite and limestone. In some areas the Torridon sandstone has been heaped on itself, sheared, and driven westward in large slices, the sandstones passing into sericitic schists and the conglomerates having their pebbles flattened and elongated, while the matrix has become full of secondary mica. Eastwards, above one of the most marked and persistent thrust-planes, the prevailing rock is a flaggy fissile micaceous gneiss or gneissose flagstone ("Moine schist," p. 707). All these rocks have a general dip and strike parallel with those of the Cambrian strata on which they now rest, and in this respect, as well as in their prevailing lithological characters, they present the most striking contrast to the rocks that unconformably underlie the quartzites a little to the west. Whatever may have been their age and original condition, they have certainly acquired their present structure since Cambrian times.

From the remarkably constant relation between the dip of the Cambrian strata and the inclination of the reversed faults which traverse them, no matter into what various positions the two structures may have been thrown, it is tolerably clear that these dislocations took place before the strata had been seriously disturbed. The persistent parallelism of the faults, folds, and prevailing strike, indicates that the faulting and tilting were parts of one continuous process. The same dominant north-easterly trend governs the structure of the whole Highlands, and reappears over the Silurian tracts of the south of Scotland and north of England. If, as is probable, it is the result of one great series of terrestrial movements, these must have occurred between the middle or close of the Cambrian period and that portion of the Old Red Sandstone period represented by the breccias and conglomerates of the Highlands. When the rocks were undergoing this metamorphism, there lay to the north-west a solid ridge of old gneiss and Torridon sandstone which offered strong resistance to plication. The thrust from the eastward against this ridge must have been of the most gigantic kind, for huge slices, hundreds of feet in thickness, were shorn off from the quartzites, limestones, red sandstones, and gneiss, and were pushed for miles to the westward. During this process, all the rocks driven forward by it had their original structure more or less completely effaced. New planes, generally parallel with the surfaces of movement, were developed in them, and along these new planes a re-arrangement and re-crystallization of mineral constituents took place, resulting in the production of crystalline schists.[1]

Much remains to be done before the structure of the Central and Southern Highlands is explained. That some portions of the rocks may belong to the Lewisian gneiss is not improbable. But, on the other hand, in almost all parts of the Highlands east of the Great Glen traces of an original fragmental or clastic origin can be detected among the schistose rocks. Zones of argillaceous shales or slates passing into andalusite-slates,[2] and of fine grit full of well-rounded fragments of quartz, felspar, or other ingredient, occur. Bands of coarse conglomerate lie on different horizons, the pebbles (granite, gneiss, &c.) being enveloped in a schistose matrix. Microscopic investigation likewise reveals, even among crystalline mica-schists, traces of the original water-worn granules of quartz in the sandy mud out of which the rocks have been formed. It is deserving of remark that the rocks along the southern margin of the Highlands are, for the most part, so little affected as closely to resemble portions of the unaltered Silurian series of the south of Scotland, and that they dip towards the mountains, becoming more highly foliated and crystalline as they recede from the lowlands. It is also noteworthy that zones of graphitic schist can be traced through different tracts of the Highlands, and that these schists and their associated strata bear a close resemblance to the carbonaceous bands associated with sedimentary deposits, such, for instance, as the Silurian anthracitic graptolite zones of the southern counties.[3]

Various eruptive rocks traverse the Highland schists, and afford interesting studies in their relation to the problems of metamorphism. Thus in Banffshire and Aberdeenshire, large masses of diorite, diabase, and gabbro cut the schists in places, but run on the whole parallel with the general strike of the region. Their appearance, though later than that of the rocks through which they have come, was earlier than the regional metamorphism. The diorite has, in many places, itself undergone great alteration. Its component crystals have ranged themselves in the direction of the prevalent foliation, and have here and there separated into distinct aggregates, the felspar forming a kind of labrador-rock, and the hornblende assuming the structure of perfect hornblende-schist. Numerous bosses of granite and porphyries likewise occur, traversing the diorites and schists and therefore of still later date. In the course of the Geological Survey of the Southern Highlands Mr. G. Barrow has found evidence that over and above the effects of great dynamical movements affecting wide tracts of country, a marked amount of metamorphism may be traced to the influence of eruptive granites and gneisses. He shows that a vast number of pegmatite veins which traverse the schists may be traced into bosses of intrusive granite or gneiss, the great mass of which is concealed below ground. He finds that three well-marked zones can be observed in the schists, of which the first, lying nearest to the main body of eruptive material, is marked by an abundance of sillimanite, the next by kyanite, and the outermost by staurolite. He has followed the same band of altered sedimentary material across these zones which are thus shown to be entirely independent of the original structure of the rocks. These observations which have been extended over many hundred square miles of Forfarshire, Perthshire, and Aberdeenshire, are of much interest and importance as they serve to connect the phenomena of contact and regional metamorphism as manifestations of one great process.[1]

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[1] *Nature*, xxxi. p. 30 ; *Quart. Journ. Geol. Soc.* xliv. (1888) p. 378. For further details see the account of pre-Cambrian rocks in Book VI. Part I. § ii.

[2] It is important to note, as showing the relation of regional to contact-metamorphism, that every stage in the development of the andalusite can be traced in these slates, though no eruptive rock appears at the surface. J. Horne, *Mineral. Mag.* 1884. I have proposed to class the metamorphic rocks of the Central and Southern Highlands by the name of Dalradian, for convenience of reference until their true geological position shall have been determined. Address to Geol. Soc., *Quart. Journ. Geol. Soc.* (1891) p. 75, and *postea*, Book VI. Part I. § ii.

[3] Among the less metamorphosed rocks that form the southern margin of the Highlands some zones of graphitic schist, together with chert bands and courses of igneous rocks, wonderfully remind the geologist of the similar assemblage of rocks in the south of Scotland. As this sheet is passing through the press Mr. Peach has detected radiolaria in these cherts, occurring much in the same way as they do in the radiolarian cherts of the southern uplands.

Greece.—In the Grecian peninsula, vast masses of chlorite-schist, mica-schist, and gneiss occur, among which thick zones of marble are interstratified. At several places in the calcareous zones fossils have been found which, though not well preserved, show that the rocks belong to the fossiliferous series of formations, and are not pre-Cambrian. These crystalline rocks in north-eastern Greece lie on the strike of normal Cretaceous hippurite limestones, sandstones, and shales, and are probably of Cretaceous age.[2]

Green Mountains of New England.—The Lower Silurian strata, which to the north in Vermont are comparatively little changed, become increasingly altered as they are traced southwards into New York Island. They are thrown into sharp folds, and even inverted, the direction of plication being generally N.N.E. and S.S.W. This disturbance has been accompanied by a marked crystallization. The limestones have become marbles, the sandy beds quartzites, and the other strata have assumed the character of slate, mica-schist, chlorite-schist, and gneiss, among which hornblendic, augitic, hypersthenic, and chrysolitic zones occur. The geological horizon of these rocks is shown by the discovery in them at various localities of fossils belonging to the Trenton and Hudson River subdivisions of the Lower Silurian system of eastern North America. The rocks have been ridged up and altered along a belt of country lying to the east of the Hudson and extending north into Canada.[3]

Menominee and Marquette regions of Michigan.—One of the most luminous essays yet published on the megascopic and microscopic proofs of dynamic metamorphism is that by G. H. Williams to which reference has already been made.[4] The author proves that a series of pre-Cambrian rocks of eruptive origin (greenstones, tuffs, agglomerates, &c.) have been converted into perfect schists. The various stages of alteration are minutely detailed, and careful drawings are given of the microscopic structures. The deductions arrived at by the author have far more than a mere local significance ; they lay an accurate basis for the study of similar "greenstone-schists" in other regions, and show how the original eruptive character of such altered rocks is to be recognised.

It may be useful to group the foregoing and a few other examples of regional metamorphism in stratigraphical order, that the student may see over how wide a range of the geological formations such transformation has taken place.

Tertiary.—Northern and Central Italy.—Nummulitic limestone rendered saccharoid, and strata (including Miocene) generally more indurated in proportion to the extent to which they have been folded and disturbed. These changes which indicate an incipient metamorphism are well displayed in the Apuan Alps and in the Apennines.[5]

Cretaceous.—Greece.—Chlorite-schist, mica-schist, marble, serpentine, &c., believed to be altered Cretaceous sandstone, shale, limestone, &c. (see above).

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[1] G. Barrow, *Quart. Journ. Geol. Soc.* 1893.

[2] M. Neumayr, *Jahrb. Geol. Reichsanst.* xxvi. (1876) p. 249. *Z. Deutsch. Geol. Ges.* xxxiii. pp. 118, 454. A. Bittner, M. Neumayr, and F. Teller, *Denksch. Akad. Wien*, xl. (1880) p. 395. This essay well deserves the attention of the student.

[3] See Dana, *Amer. Journ. Sci.* iv. v. vi. xiii. xiv. xvii. xviii. xix. xx. ; *Q. J. Geol. Soc.* 1882, p. 397. The identification of the so-called Taconic schists of New England with altered Lower Silurian rocks has been called in question by Sterry Hunt, but the stratigraphical evidence collected by A. Wing, Dana, and others, and the testimony of the fossils collected by Dana, Dwight, &c., have sustained it. In the Punjab a series of gneisses and schists overlies infra-Triassic rocks. Wynne, *Geol. Mag.* 1880, p. 314.

[4] *Bull. U.S. Geol. Survey*, No. 62, 1890.

[5] Lotti and Zaccagna, *Boll. Comit. Geol. d'Italia*, 1881, p. 5. Lotti, *ibid.* p. 419, *Bull. Soc. Géol. France*, xvi. (1888) p. 406.

Coast range of California.—Strata containing Cretaceous fossils pass into jaspers, siliceous slate, (phthanites), glaucophane-schist, garnetiferous mica-schist, serpentine, &c.[1]

Jurassic.—Alps.—Sericite-schists, altered limestones, &c. (p. 622).

Sierra Nevada (California).—Clay-slates, talcose slates, serpentine, &c., passing into rocks containing Jurassic fossils.[2]

Trias.—Sierra Nevada (Spain).—Clay-slate, mica-schists, talc-schists, and limestones.[3]

Carrara.—Mica-schist, talc-schist, marbles, passing down into limestones containing *Encrinus liliiformis, Phylloceras, Pentacrinus,* below which lie gneissic and other schists enclosing *Orthoceras, Actinoceras,* and evidently of Palæozoic age.[4]

Alps.—Limestones, dolomites, and gypsums rendered crystalline, associated with calc-mica-schist and other varieties of schist.

Carboniferous.—Alps.—Graphite-schist, phyllite-gneiss, &c. (p. 622).

Eastern Brittany.—Carboniferous shales altered into crystalline schists.[5]

Devonian.—Taunus.—A large series of crystalline schists (p. 620).

Ardennes.—Crystalline schists with garnet, hornblende, mica, &c. (p. 619).

Silurian.—Norway.—A series of schists resembling those of Scotland, lying upon and interstratified with fossiliferous beds (p. 621).

Green Mountains of New England.—A great group of schists and limestones, with fossils in some beds (p. 628).

Northern Alps.—Upper Silurian fossils among gneiss, diorite-schist, mica-schist, chloritoid-schist, &c.[6]

Cambrian and Silurian.—Scotland.—A great series of crystalline schists overlying quartzite and limestones with fossils (p. 624).

Saxon granulite tract.—Schists, schistose conglomerates, &c.[7]

South Wales.—A fine foliation of the tuffs, representing an early stage of regional metamorphism.[8]

Pre-Cambrian, (*Archæan*).—Scotland.—Sandstone and arkose passing into lustrous crumpled micaceous schists (p. 544). Some of the Archæan gneisses and hornblende-rocks of Sutherland have had a new schistosity superinduced in them by the shearing movements that altered the Cambrian strata (p. 627).

Summary.—From the evidence now adduced the following conclusions may be confidently drawn.

1. There are wide regions in which crystalline schists (*a*) overlie fossiliferous strata, or (*b*) contain intercalated bands in which fossils occur, or (*c*) pass either laterally or vertically into undoubted sedimentary strata.

2. These schists are in some cases the metamorphosed equivalents of what were once ordinary sedimentary deposits, including sometimes associated igneous rocks.

3. The alteration by which rocks have been affected in regional metamorphism is similar in its stages to what may be traced in local metamorphism round bosses of granite, but has attained a much greater development.

4. Regional metamorphism has been directly connected with intense compression or tension, and is usually most pronounced where, as shown

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[1] Whitney, *Geol. Surv. California,* 'Geology,' vol. i. p. 23. G. F. Becker, *Amer. Journ. Sci.* xxxi. (1886) p. 348; 'Geology of the Quicksilver Deposits of the Pacific Slope,' Monograph No. xiii. of *U.S. Geol. Survey,* 1888.

[2] Whitney, *op. cit.* p. 225.

[3] De Verneuil, *Bull. Soc. Géol. France* (2), xiii. p. 708. R. von Drasche, *Jahrb. Geol. Reichsanst.* xxix. (1879) p. 93. The identification of these rocks with Triassic beds is a probable conjecture.

[4] Coquand, *Bull. Soc. Géol. France* (3), iii. p. 26; iv. p. 126. Zaccagna, *Boll. Com. Geol. Ital.* xii. (1881) p. 476. Lotti, *op. cit.* p. 419 and plate ix.

[5] Jannettaz, *Bull. Soc. Géol. France* (3), ix. (1881) p. 649.

[6] M. Vacek and Baron Foullon, *Jahrb. Geol. Reichsanst.* xxxiv. (1884) pp. 609, 635. G. Stache, *Z. Deutsch. Geol. Ges.* 1884, p. 277.

[7] Lehmann's work cited *ante,* p. 156.

[8] *Q. J. Geol. Soc.* xxxix. (1883) p. 310.

by plication, puckering, shear-structure, and the crushing down of the component minerals, the rocks have been subjected to the greatest mechanical movement.

5. The dynamical strain has been generally, perhaps always, accompanied with more or less chemical reaction, not, as a rule, involving the introduction of new chemical constituents, but consisting chiefly in a recombination of those already present in the rocks, with the consequent development of new crystalline minerals.

6. This chemical and mineralogical rearrangement has probably been superinduced under the influence of moderate heat, and in presence of water, and is comparable with what, on a feeble scale, can be achieved in the laboratory.

7. The alteration of rocks in an area of regional metamorphism is often strikingly unequal in degree even over limited areas, being apt to attain sporadically a maximum intensity, particularly in tracts of greatest shearing or plication, while in other areas, the original clastic or crystalline characters may be easily discernible.

8. The nature of the alteration has depended first, and chiefly, on the original character and structure of the rocks affected by it: and secondly, on the nature and intensity of the metamorphic activities. Of some rocks (sandstone, carbonaceous shale, coal), the original condition may be recognisable when that of their associated strata has entirely disappeared.

9. The foliation in a tract of regional metamorphism has been developed along divisional planes which guided the crystallization or rearrangement of the minerals. In some cases, these planes coincide with those of original deposit. In others, they may represent cleavage, as pointed out by Sedgwick and Darwin. Or they may indicate the planes along which, under intense pressure, the longer axes of crystallizing minerals would naturally range themselves. In a rock, homogeneous in chemical composition and general texture, foliation might be induced along any dominant divisional planes. If these planes were those of cleavage or of shearing, the resultant foliation might not appreciably differ from that along original bedding planes.[1] But it may be doubted whether a cleavage foliation of clastic sedimentary strata could run over wide areas without sensible and even very serious interruptions. In most large masses of sedimentary matter, the usual alternations of different kinds of sediment could not but produce distinct kinds of rock under the influence of metamorphic change. Where foliation coincides with cleavage over large tracts, it will almost certainly be crossed by bands, more or less distinct, coincident with the original bedding whether of sedimentary or of eruptive rocks, and running oblique to the general foliation, as bedding and cleavage do, save where they may happen to coalesce. Where a massive rock of generally homogeneous composition, such as a felsite or granite, has been intensely sheared, a re-arrangement or re-crystallization of its minerals has taken place along the planes of shearing. Such a rock is thus transformed into a schist. Even rocks

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[1] Jannettaz points out that the cleavage of the slates in the Grenoble Alps is parallel to the foliation of the mica-schists. *Bull. Soc. Géol. France* (3), ix. (1881) p. 649.

of much more varied structure, like Archæan gneisses, have been subjected to such changes from shearing as not only to lose entirely their original structure, but to acquire a new foliation parallel to the shearing planes.

It is now generally agreed that gneisses and many forms of schist have been formed by dynamical action from deep-seated masses of igneous rocks, both acid and basic. The banding of these rocks, which was formerly regarded as evidence of aqueous deposition, is no doubt generally due to an original segregation of the component minerals of still unconsolidated igneous rocks, like the segregation-veins described on p. 580, though it may to some extent have resulted from the re-arrangement and re-crystallization of the materials of such rocks under intense mechanical strain. The occurrence of lenticular bands or bosses of amphibolite in gneiss may point to dykes of some hornblendic rock by which the original granite was traversed before the development of the foliated structure. A similar connection can be traced between masses of diorite, gabbro, &c., and hornblende-schists, gabbro-schists, &c. The granitoid character of these rocks, under the great stresses they have suffered during periods of terrestrial disturbance, has here and there entirely disappeared. First the minerals (especially the felspars) are seen to have ranged themselves with their long axis in one general direction. Then they separate into layers or folia in the same direction, and acquire a more or less distinctly foliated structure. Thus, a massive diorite, gabbro, or diabase has been converted into amphibolite-schist, sometimes with bands of massive labradorite.[1]

PART IX. ORE DEPOSITS.[2]

Metallic ores and other minerals that are extracted for their economic value occur in certain well-marked forms which have been variously classified; but for the purposes of the geological student it is most convenient to consider them from the point of view of geological structure and history. Thus arranged, they naturally group themselves into three great series; 1st, those contemporaneously deposited among stratified formations; 2nd, those contemporaneously formed with the other ingredients of crystalline (massive and schistose) rocks; 3rd, those subsequently introduced by infiltration or otherwise into fissures, caverns, or other spaces of any kind of rock.

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[1] The idea suggested many years ago by Jukes ('Student's Manual of Geology'), that the hornblendic bands of the crystalline schists might have been originally eruptive rocks, has been confirmed by more recent work. See Lehmann's 'Entstehung der altkrystallinischen Schiefergesteine'; Allport, *Q. J. Geol. Soc.* xxxii. (1876) p. 425; the diorites of the north of Scotland, *ante*, p. 627, and paper by G. H. Williams, cited on p. 617.

Besides the works already cited on Metamorphism the student may consult the following: Delesse, *Mém. Savans Étrangers*, xvii. Paris, 1862, pp. 127-222; *Ann. des Mines*, xii. (1857); xiii. (1858); 'Études sur le Métamorphisme des Roches,' Paris, 1869; Durocher, 'Études sur le Métamorphisme des Roches,' *Bull. Soc. Géol. France* (2), iii. (1846); Daubrée, *Ann. des Mines*, 5^{me} série, xvi. p. 155; Bischof, 'Chemical Geology,' chap. xlviii.; J. Roth, *Abhandlungen Akad. Berlin*, 1871; 1880; Gümbel, 'Oestbayerische Grenzgebirge,' 1868; H. Credner, *Zeitsch. Gesammt. Naturwiss.* xxxii. (1868) p. 353; *N. Jahrb.* 1870, p. 970; A. Inostranzeff, 'Studien uber metamorphosirte Gesteine,' Leipzig, 1879.

[2] The best English work on this subject is 'Ore Deposits,' by J. A. Phillips, 1884. The following works on ores and mining may also be consulted: B. von Cotta, 'Die Lehre von Erzlagerstatten,' 1859-61; A. von Groddeck, 'Die Lehre von den Lagerstätten der Erze,' 1879; W. Forster, 'Treatise on a Section of the Strata from Newcastle-on-Tyne to Cross Fell'; W. Wallace, 'Laws which regulate the deposition of Lead Ores,' 1861; F. von Sandberger, 'Untersuchungen über Erzgänge'; numerous valuable papers by J. W. Henwood and others in *Trans. Roy. Geol. Soc. Cornwall*; G. F. Becker, 'Geology of the Comstock Lode,' *U.S. Geol. Survey*, Monographs iii. iv.; also 'Quicksilver Deposits,' *8th*

1. Contemporaneous ores of stratified rocks have been deposited in water, together with the sandstones, limestones, or other strata among which they lie. In some cases, they are mere mechanical sediments, such as the auriferous gravels of California and Australia (placer-works) or the stream-tin deposits of Cornwall, obviously derived from the disintegration of older rocks, principally veinstones, in which the ores were developed. In other cases, they result from the accumulation of chemical precipitates, as in the modern deposition of iron-ore on the floors of lakes and beneath bogs. These precipitates may either of themselves form independent mineral masses, or may serve as impregnations of other stratified deposits, like the copper ores that occur so abundantly diffused through the Kupfer-Schiefer of Saxony. In all these instances, the metalliferous rocks belong to the stratified type of geological structure (p. 498 *seq.*) They occur in layers varying from mere films up to beds or stratified masses of great thickness. In some cases, they retain the same average thickness for long distances, in others, they swell out or die away rapidly, or occur in scattered concretions. Organic remains are commonly associated with ores of this type.

2. Contemporaneous ores of crystalline rocks are exemplified by the beds of iron-ore, pyrites, &c., that so frequently occur intercalated among the crystalline schists. They lie as massive sheets or thin partings, and usually present a conspicuously lenticular character. That they were formed contemporaneously with the layers of quartz, mica, felspar, hornblende, or other minerals among which they lie, and owe their crystalline structure to the same process that produced the characteristic foliation of the crystalline schists, may usually be inferred with considerable certainty, though cases not infrequently arise where it is difficult or impossible to draw any line between this type and that of true subsequently-formed veins. Besides these lenticular ores of the crystalline schists, the massive rocks also contain contemporaneously crystallized ores. The diffused magnetite and titaniferous iron of the basalts, diabases, &c., and the occasional separation of the ore in the layers of segregation-veins in these rocks are familiar illustrations. Large included masses of these and other ores are sometimes available for mining (*ante*, p. 70).

3. Subsequently introduced ores are distinguished by the contrast between their contents and structure and those of the rocks through which they pass. They have been deposited, subsequent to the consolidation of these rocks, in cavities previously opened for their reception. In certain rocks (limestones, dolomites, &c.), intricate channels and large

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Ann. Rep. U.S. Geol. Survey, 1886-87, p. 965, and Monograph xiii.; R. D. Irving, 'Copper-bearing rocks of Lake Superior,' *Ann. Rep. U.S. Geol. Survey*, 1881-82, p. 93 and Monograph v.; 'Gîtes Minéraux,' E. Fuchs et L. Delaunay, Paris, 1893.

irregular caverns have been dissolved out by the solvent action of underground water; in other cases, fissures have been formed by fracture, or the rocks, exposed to great compression, have been puckered up or torn asunder, so that irregular spaces have been opened in them. Metallic ores and crystalline minerals introduced by infiltration, sublimation, or otherwise, into the cavities formed in any of these ways, may be grouped, according to the shape of the cavity, into veins or lodes, which have filled up vertical or highly inclined fissures, and stocks, which are indefinite aggregations often found occupying the place of subterranean cavities.

The first two of these three types of ore deposits do not require special treatment here. The stratified type has the usual character of sedimentary formations (Book IV. Part I.); the crystalline type forms part of the structure of schistose and massive rocks (Book II. Part II. Sect. vii. §§ 2 and 3; and Book VI. Part I. § i.); the third type, however, from its economic importance and its geological interest, merits some more detailed notice.

§ i. Mineral-Veins or Lodes.

A true mineral-vein consists of one or more minerals deposited within a fissure of the earth's crust, and is usually inclined at from 10° to 20° from the vertical. The bounding surfaces of such a vein are termed walls, and, where inclined, that which is uppermost is known as the *hanging*, and that which is lowest as the *lying* or *foot* wall. The surrounding rock, through which veins run, is termed the country or country-rock. A vein may coincide with a line of fault or of joint, or may run independent of any other structural divisions; in all cases it is independent of the bedding or foliation of the "country." Cases occur among crystalline massive rocks, however, and still more frequently among limestones, where the introduction of mineral matter has taken place along gently inclined or even horizontal planes, such as those of stratification, and the veins then look like interstratified beds. Mineral-veins are composed of masses or layers of simple minerals or metallic ores alternating, or more irregularly intermingled with each other, distinct from the surrounding rock, and evidently the result of separate deposition. They are in no respect to be confounded with veins of rock injected in a molten condition from below, or segregated from a surrounding pasty magma into cracks in its mass. But they are commonly most frequent and most metalliferous in districts where eruptive rocks are abundant.

Variations in breadth.—Mineral-veins vary in breadth from a mere paper-like film up to a great wall of rock 150 feet wide or more. The simplest kinds are the threads or strings of calcite and quartz, so frequently to be observed among the more ancient, and especially more or less altered, rocks. These may be seen running in parallel lines, or ramifying into an intricate network, sometimes uniting into thick branches and again rapidly thinning away. Considerable variations in breadth may be traced in the same vein. These may be accounted for by unequal solution and removal of the walls of a fissure, as in the action of permeating water upon a calcareous rock; by the irregular opening of a rent, or by a shift of the walls of a sinuous or irregularly defined fissure. In the last-named case, the vein may be strikingly unequal in breadth, here and there nearly disappearing by the convergence of the walls, and then rapidly swelling out and again diminishing. How simply this irregularity may be accounted for will be readily perceived by merely copying the line of such an uneven fissure on tracing paper and shifting the tracing along the line of the original. If, for example, the fissure be assumed to have the form shown at *a b*, in the first line (Fig. 312), a slight shifting of one side to the right, as at *a' b'* in the second line, will allow the two opposite walls to touch at only the points *o o*, while open spaces will be left at *c c d*. A movement to the same extent in the reverse direction would give rise to a more continuously open fissure, as in the third line. That shiftings of this nature have occurred to an enormous extent in the fissures filled with mineral-veins, is shown by their abundant slickensides (p. 526). The polished and striated walls have been coated with mineral matter, which has subsequently been similarly polished and grooved by a renewal of the slipping.

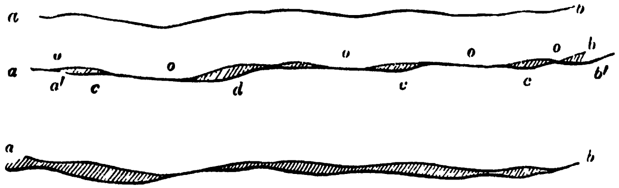

Fig. 312.—Widening of a fissure by relative shifting of its side (De la Beche).

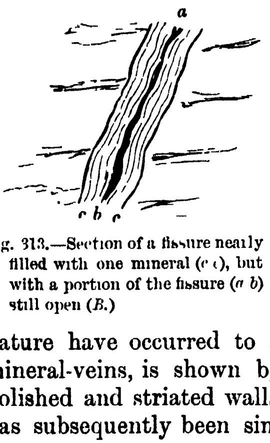

Fig. 313.—Section of a fissure nearly filled with one mineral (*c c*), but with a portion of the fissure (*a b*) still open (*B.*)

Structure and contents.—A mineral-vein may be either simple, that is, consisting entirely of one mineral, or compound, consisting of several; and may or may not be metalliferous. The minerals are usually crystalline, but layers or irregular patches of soft decomposed earth, clay, &c., frequently accompany them, especially as a layer on the wall-face (*flucan*). The non-metalliferous minerals are known as gangue or veinstones, the more crystalline being often also popularly classed as spars. The metal-bearing minerals are known as ores. The commonest veinstones are quartz (usually either crystalline or crypto-crystalline, with numerous fluid-inclusions), calcite, barytes, and fluorite. The presence of silica is revealed not only by the quartz, but by the hard siliceous bands so often observable along the walls of a vein. These can often be determined to be portions of the "country" which have been indurated by the deposition of silica in their pores. The ores are sometimes native metals, especially in the case of copper and gold; but for the most part are oxides, silicates, carbonates, sulphides, chlorides, or other combinations. Some of the contents of mineral-veins are associated with certain minerals more usually than with others, as galena with blende, pyrite with chalcopyrite, gold with quartz, magnetite with chlorite. Of the manner in which the contents of a mineral-vein are disposed the following are the chief varieties.

(1) **Massive.**—Showing no definite arrangement of the contents. This structure is especially characteristic of veins consisting of a single mineral, as of calcite, quartz, or barytes. Some metalliferous ores (pyrites, limonite) likewise assume it.

(2) **Banded, comby,** in parallel (and sometimes exactly duplicated) layers or combs. In this common arrangement, each wall (*a a*, Fig. 314) may be coated with a layer of the same material, perhaps some ore or flucan (*b b*), followed on the inside by another layer (*c c*), perhaps quartz, then by layers of calcite, fluor-spar, or other veinstone, with strings or layers of ore, to the centre, where the two opposite walls may be finally united by the last zone of deposit (*i*). Even where each half of the vein is not strictly a duplicate of the other, the same parallelism of distinct layers may be traced.

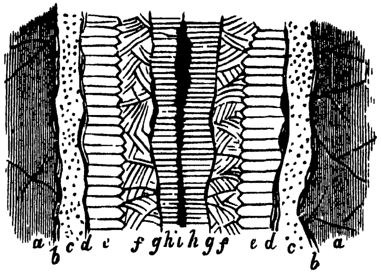

Fig. 314.—Section of Mineral-Vein with symmetrical disposition of duplicate layers.

(3) **Brecciated,** containing angular fragments of the surrounding "country," cemented in a matrix of veinstones or ores. It may often be observed that these fragments are completely enclosed within the matrix of the vein, which must have been partially open, with the matrix still in course of deposit, when they were detached from the parent rock. Large blocks (*riders*) may be thus enclosed.

(4) **Drusy,** containing or made up of cavities lined with crystalline minerals. The central parts of veins frequently present this structure, particularly where the minerals have been deposited from each side towards the middle.

(5) **Filamentous,** having the minerals disposed in thread-like veins; this is one of the commonest structures.

Metallic ores occur under a variety of forms in mineral-veins. Sometimes they are disseminated in minute grains or fine threads (gold, pyrites), or gathered into irregular strings, branches, bunches, or leaf-like expansions (native copper), or disposed in layers alternating with the veinstones parallel with the walls of the vein (most metallic ores), or forming the whole of the vein (pyrites, and occasionally galena), or lining drusy cavities, both on a small scale and in large chambers (hæmatite, galena). Some ores are frequently found in association (galena and blende), or are noted for containing minute proportions of another metal (argentiferous galena, auriferous pyrites).

Successive infilling of veins.—The symmetrical disposition represented in Fig. 314 shows that the fissure had its two walls coated first with the layers *b b*. Thereafter the still open, or subsequently widened, cleft received a second layer (*c c*) on each face, and so on progressively until the whole was filled up, or until only cavernous spaces (druses) lined with crystals were left. In such cases, no evidence exists of any terrestrial movement during the process of successive deposition. The fissure may have been originally as wide as the present vein, or may have been widened during the accumulation of mineral matter, so gradually and gently as not to disturb the gathering layers. But in many instances, as above stated, proofs remain of a series of disturbances whereby the formation of the vein was accelerated or interrupted. Thus at the Wheal Julia Lode, Cornwall, the central zone (*e* in Fig. 315) is formed of quartz-crystals pointing as usual from the sides towards the centre of the vein, but it is only one of five similar zones, each of which marks an opening of the fissure and the subsequent closing of it by a deposit of mineral matter along the walls.[1] The occurrence of different layers on the two walls of a vein may sometimes indicate successive openings of the fissure. In Fig. 316 the fissure at one time, no doubt, extended no farther than between 1 and 2. Whether the band of copper pyrites had already filled up the fissure, previous to the opening which allowed the deposit of the silica, or was introduced into a fissure opened between 2 and 3 after the deposit of the silica, is uncertain.[2]

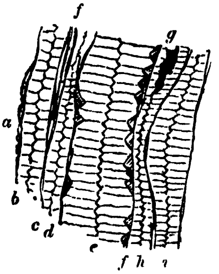

Fig. 315.—Section of Wheal Julia Lode, Cornwall, showing five successive openings of the same fissure (*B.*)

a f f, Copper-pyrites and blende; *b*, *d*, *e*, *h*, *i*, quartz in crystals pointing inwards; *c*, clay; *g*, empty space.

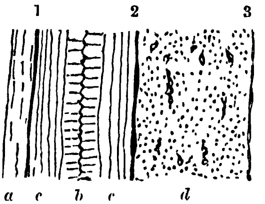

Fig. 316.—Section of part of a Lode, Godolphin Bridge, Cornwall (*B.*)

a, Quartz coating cheek of vein; *b*, quartz-crystals pointing inward; *c c*, agatiform silica; *d*, thick layer of copper-pyrites.

The occurrence of rounded pebbles of slate, quartz, and granite in the lodes of Cornwall at depths of 600 feet from the surface, of gneiss in the vein at Joachimsthal at 1150 feet, and of Liassic land and freshwater shells at 270 feet in veins traversing the Carboniferous Limestone of the Mendip Hills and South Wales, seems to indicate that fissures may remain sufficiently open to allow of the introduction of water-worn stones and terrestrial organisms from the surface even down to considerable depths.[3]

Connection of veins with faults and cross-veins.—While the interspaces between any divisional planes in rocks may serve as receptacles of mineral depositions, the largest and most continuous veins have for the most part been formed in lines of fault. These may be traced, sometimes in a nearly straight course, for many miles across a country, and as far downward as mining operations have been able to descend. Sometimes veins are themselves faulted and crossed by other veins. Like ordinary faults also, they are apt to split up at their terminations.

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[1] De la Beche, 'Geol. Obs.' p. 698.

[2] De la Beche, *op. cit.* p. 699.

[3] De la Beche, *op. cit.* p. 696. Moore, *Q. J. Geol. Soc.* xxiii. 483; *Brit. Assoc.* 1869, p. 360.

These features are well exhibited in some of the mining districts of Cornwall (Fig. 317).

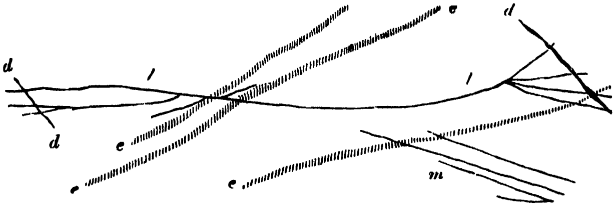

Fig. 317.—Plan of Wheal Fortune Lode, Cornwall (*B.*)
l l m, lodes of which the main one splits up towards east and west, traversing elvan dykes, *e e*, but cut by faults or cross-courses, *d d*. Scale one inch to a mile.

The intersections of mineral-veins do not always at once betray which is the older series. If a vein has really been shifted by another, it must of course be older than the latter. But the evidence of displacement may be deceptive. In such a section as that in Fig. 318, for example, a cursory examination might suggest the inference that the vein *d e* must be later than the dyke or vein *a b*, by which its course appears to have been shifted. Should more careful scrutiny, however, lead to the detection of the vein crossing the supposed later mass at *c*, it would be clear that this inference must be incorrect.[1] In mineral districts, different series or systems of mineral-veins can generally be traced, one crossing another, belonging to different periods, and not infrequently filled with different ores and veinstones. In the south-west of

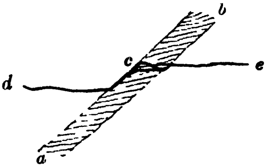

Fig. 318.—Deceptive shifting of a Vein (*B.*)

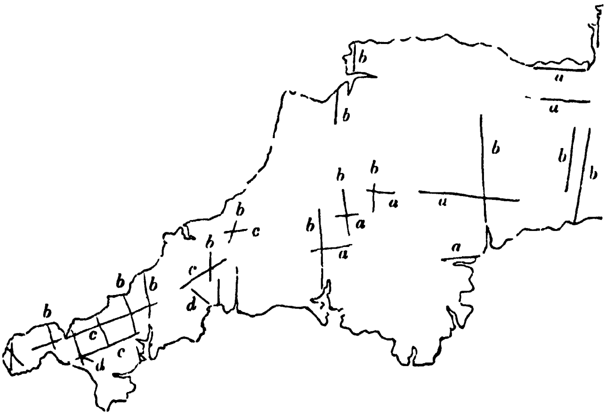

Fig. 319.—General Map of Fissures in the mineral tracts of S.W. England (*B.*)

England, for example, a series of fissures running N. and S., or N.N.W. and S.S.E., traverses another series, which runs in a more east and west direction (W.S.W. to E.N.E., or W.N.W. to E.S.E.) The latter (*c c*, *d d*, Fig. 319) in Cornwall contain the chief copper and tin ores, while the cross-courses (*b b*) contain lead and iron. The east and west lodes in the west part of the region were formed before those which cross them, for they are shifted, and their contents are broken through by the latter. To the east, near Exeter, the east and west faults *a a* are later than the New Red Sandstone, and in Somerset than the Lias.[1]

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[1] De la Beche, *op. cit.* p. 657.

Relation of contents of veins to surrounding rock.—It has long been familiar to miners that where a vein traverses various kinds of "country" it is often richer in ore when crossing or touching some rocks than others. In the north of England, for example, the galena is always most abundant in the limestones and scarcest in the shales, the veins in the Great Limestone (which is 150 feet thick or less) having produced as much lead as all the rest of a mass of 2000 feet of strata put together. In Cornwall and Devon, it has been observed that some lodes yield tin where they cross granite, and copper where they traverse slate; the same lode, as at Botallack, may cross three times from the one rock into the other, and each time the same change of metallic contents takes place. Some of the lodes, which are poor in ore in the slate, become rich as they cross an elvan (Fig. 320), or, on the other hand, the ore is so split up into strings in the elvan, as to be much less valuable than in the slate. Similar variations in the nature or amount of ores and veinstones with the character of the rocks traversed by mineral-veins have been generally observed in mining districts, even among the most diverse geological formations. Chemical analysis has revealed the presence of minute quantities of metallic ores dispersed through the substance of the rocks surrounding mineral-veins. By isolating some of the more frequent silicates found as rock-constituents (such as augite, hornblende, and mica), iron, nickel, copper, cobalt, arsenic, antimony, tin, &c., have been found in appreciable quantity, and the conclusion has been drawn by F. Sandberger that the heavy metals are present in the silicates of the crystalline rocks of all geological periods. Stratified rocks also, when subjected to sufficiently delicate analysis, reveal the presence in them of the metals and non-metallic substances that constitute mineral-veins. Clay-slates, for example, have been found to contain copper, zinc, lead, arsenic, antimony, tin, cobalt, nickel.[2]

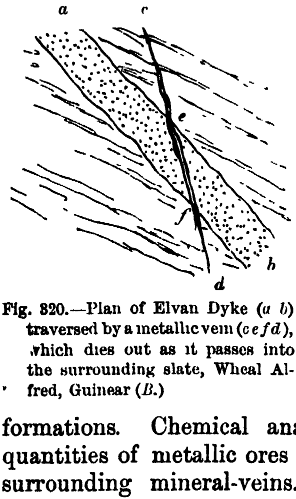

Fig. 320.—Plan of Elvan Dyke (*a b*) traversed by a metallic vein (*c e f d*), which dies out as it passes into the surrounding slate, Wheal Alfred, Guinear (*B.*)

Decomposition and recomposition in mineral-veins.—It has been noticed that the "country" through which mineral-veins run is often considerably decomposed. In Cornwall, this is specially observable in the granite. Round the Comstock Lode also, the diabase is particularly decayed. Moreover, in most mineral-veins there occur layers of clay, earth, or other soft friable loamy substances, to which various mining names are given. The great majority of the remarkable minerals of the south-west of England occur in those parts of the lodes where such soft earths abound. The veins evidently serve as channels for the circulation of water both upward and downward, and to this circulation the decay of some bands into mere clay or earth, and the recrystallization of part of their ingredients into rare or interesting minerals, are to be ascribed. It is observable, also, that the upper parts of pyritous mineral-veins, as they approach the surface of the ground, are usually more or less decomposed from the infiltration of meteoric water, siliceous peroxide of iron and limonite being especially predominant. (Gossan of Cornwall, Chapeau de Fer, Eiserner Hut.)

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[1] De la Beche, *op. cit.* p. 659.

[2] This question has been made the subject of an exhaustive research by Prof. F. Sandberger, 'Untersuchungen über Erzgänge,' Part i.

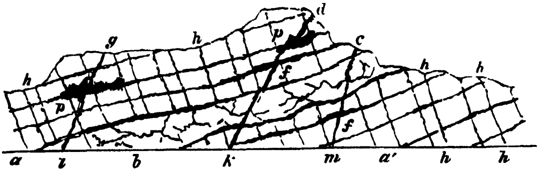

Fig. 321.—Section of Mineral deposits in limestone, Derbyshire (*B.*)

a a′, Carboniferous Limestone with intercalated bed of pyroxenic lava or "toadstone' (*b*), *h h h h*, joints traversing the limestone, *i g*, *k d*, *m c*, veins traversing all the rocks and containing veinstones and ores; *f*, spaces between the beds enlarged by solution and filled with minerals or ores ("flat-works"); *p p*, large irregular cavernous spaces dissolved out of the rock and filled with minerals and ores.

§ ii. Stocks and Stock-works. (Stöcke, Stockwerke.)

Cavernous spaces dissolved out in such rocks as limestone, or caused by rupture or otherwise, may be of indeterminate shape, and may be filled with one or more veinstones or ores, either in symmetrical zones following the outline of walls, floor, and roof, or in parallel and roughly horizontal bands (Fig. 321). Irregular metalliferous masses of this kind have long been known in Germany by the name of Stocks (Stöcke) when of large size, smaller aggregations being known as *Butzen* (cones) and *Nester* (tufts). The size of these indefinite accumulations of ore varies from mere nests up to masses 800 feet or more in one direction by 200 feet or more in another. Hæmatite, brown iron-ore, and galena not infrequently occur in this form in limestone, as in the "pockets" of hæmatite and "flat-works" of galena in the Carboniferous Limestone, and more notably in the ore "chambers" of the Eureka and Richmond mines of Nevada, and the Emma, Flagstaff, and other mines in Utah, from which, in recent years, such vast quantities of ore have been obtained. The "gash" or "rake" veins of galena in the north of England occur in vertical joints of limestone which have been widened by solution, and are sometimes completely cut off underneath by the floor of shale or sandstone on which the limestone lies. Lenticular aggregations of ore and veinstone found in granite, as in the south-west of England, where they are known as Carbonas, cannot be due to the infilling of chambers dissolved by subterranean solution. They are usually connected with true fissure-veins; but their mode of origin is not well understood.

Stock-works are portions of the surrounding rock or "country" so charged with veins, nests, and impregnations of ore that they can be worked as metalliferous deposits. The tin stock-works of Cornwall and Saxony are good examples. Sometimes a succession of such stock-works may be observed in the same mine. Among the granites, elvans, and Devonian slates of Cornwall, tin-ore has segregated in rudely parallel zones or "floors." At Botallack, at the side of ordinary tin lodes, floors of tin-ore from six to twelve feet thick and from ten to forty feet broad occur. The name of *Fahlbands* has been given to portions of "country" which have been impregnated with ores along parallel belts.

Origin of mineral-veins.—Various theories have been proposed to account for the infilling of mineral veins. Of these the most noteworthy are—(1) the theory of lateral segregation,—which teaches that the substances in the veins have been derived from the adjacent rocks by a process of leaching, or solution and redeposit; and (2) the theory of infilling from below,—according to which the minerals and ores were introduced (*a*) dissolved in water or steam, or (*b*) by sublimation, or (*c*) by igneous fusion and injection.

The structure and characteristic mineral combinations of metalliferous veins are precisely such as would be produced by deposition from aqueous solution. There can hardly be now any doubt that the contents of these veins have generally been deposited by water. But the source from which the metals were derived is not so obvious. The fact that the nature and amount of the minerals, and especially of the ores, in a vein so often vary with the composition of the surrounding rocks shows that these rocks have had an influence on the precipitation of mineral matter in the fissures passing through them, if they were not themselves the source from which the metals were obtained; for, as already remarked, the presence of the heavy metals has now been detected in rocks of almost every kind and age. On the other hand, in some volcanic districts at the present time, various minerals, including silica, both crystalline and chalcedonic, metallic sulphides, and even metallic gold, are being deposited in fissures up which hot water rises.[1] Each of these modes of origin may in different cases have occurred. It is almost certain, from what we now know of the diffusion of metallic substances, that there must be a decomposition of the rocks on either side of a fissure, perhaps to a great distance, and that a portion of the mineral matter abstracted will be laid down in another form along the fissure-walls. If, on the other hand, the rocks on either side of the fissure are permeated for some distance by hot ascending waters, holding such metalliferous solutions as have been detected in the hot springs of California and Nevada, some of the dissolved mineral substances will doubtless be deposited in the fissure, and may even be introduced into the pores and cavities of the adjacent rocks.[1]

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[1] See J. A. Phillips, *Q. J. Geol. Soc.* xxxv. p. 390.

PART X. UNCONFORMABILITY.

Where one series of rocks, whether of aqueous or igneous origin, has been laid down continuously and without disturbance upon another series, they are said to be *conformable*. Thus in Fig. 322, the sheets of conglomerate (*b b*) and clays and shales (*c d*), have succeeded each other in regular order, and exhibit a perfect *conformability*. They *overlap* each other, however, each bed extending beyond the edge of that below it, and thereby indicating a gradual subsidence and enlargement of the area of deposit (p. 518). But all these conformable beds repose against an older platform *a a*, with which they have no unbroken continuity. Such a surface of junction is called an *unconformability*, and the upper are said to lie *unconformable* on the lower rocks. The latter may consist of horizontal or inclined clastic strata, or contorted schists, or eruptive massive rocks. In any case, there is a complete break between them and the overlying formation, the beds of which rest successively on different parts of the older mass.

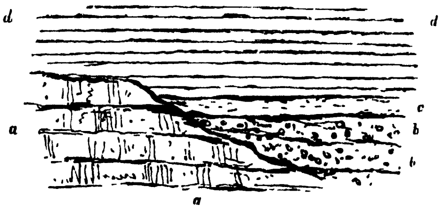

Fig. 322.—Unconformability among horizontal strata. Lias resting on Carboniferous Limestone, Glamorganshire (*B.*)

It is evident that this structure may occur in ordinary sedimentary, igneous, or metamorphic rocks, or between any two of these great series. It is most familiarly displayed among clastic formations, and can there be most satisfactorily studied, since the lines of bedding furnish a ready means of detecting differences of inclination and discordance of superposition. But even among igneous protrusions, and in ancient metamorphic masses, distinct evidence of unconformability is occasionally traceable. Wherever one series of rocks is found to rest upon a highly denuded surface of an older series, the junction is unconformable.[2]

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[1] Henwood, *Address Roy. Inst. Cornwall*, 1871. J. A. Phillips, *Phil. Mag.* November 1868, December 1871, July 1873, March 1874 ; 'Ore Deposits,' 1884, p. 73. J. S. Newberry, *School of Mines Quarterly*, New York, March 1880. J. A. Church, 'The Comstock Lode,' 4to, New York, 1879. Sterry Hunt, 'Chemical and Geological Essays,' 1875, p. 183. Brough Smyth's 'Goldfields of Victoria,' Melbourne, 1869. F. Sandberger, 'Untersuchungen über Erzgange,' part i.

[2] The occurrence of considerable contemporaneous erosion between undoubtedly conformable strata belonging to one continuous geological series has already (pp 504-506) been described.

Hence, an uneven irregularly-worn platform below a succession of mutually conformable rocks is one of the most characteristic features of this kind of structure.

It has already been pointed out, that though conformable rocks may usually be presumed to have followed each other continuously without any great disturbance of geographical conditions, we cannot always be safe in such an inference. But an unconformability leaves no room to doubt that it marks a decided break in the continuity of deposit. Hence no kind of geological structure is of higher importance in the interpretation of the history of the stratified formations of a country. In rare cases, an unconformability may occur between two horizontal groups of strata. On the left side of Fig. 322, for instance, the beds *d* follow horizontally upon the horizontal beds (*a*). Were merely a limited section visible, disclosing only this relation of the rocks, the two groups *a* and *d* might be mistaken for conformable portions of one continuous series. Further examination, however, would lead to the detection of evidence that the limestone *a* had been upraised and unequally denuded before the deposition of the overlying strata *b c d*. This denudation would show that the apparent conformability was merely local and accidental, the older rock having really been upraised and worn down before the formation of the newer. In such a case, the upheaval must have been so uniform over some tracts as not to disturb the horizontality of the lower strata, so that the younger deposits lie in apparent conformability upon them.

As a rule, however, it seldom happens that movements of this kind have taken place over an extensive area so equably as not to produce a want of coincidence somewhere between the older and newer rocks. Most frequently, the older formations have been tilted at various angles, or even placed on end. They have likewise been irregularly and often enormously worn down. Hence instead of lying parallel, the younger beds run transgressively across the upturned denuded ends of the older. The greater the disturbance of the older rocks, the more marked is the unconformability. In Fig. 323, the lower series of beds (*c*) has been upturned and denuded before the deposition of the upper series (*a b*) upon it. In this instance, the upper worn surface of the limestones (*c*) has been perforated by boring mollusks below the sandy stratum (*b*).

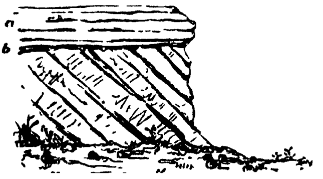

Fig. 323.—Unconformability between horizontal and inclined strata. Inferior Oolite (*a b*) resting on Carboniferous Limestone (*c*); Frome, Somerset (*B.*)

An unconformability forms one of the great breaks in the geological record. In Fig. 221 (p. 518), by way of illustration, we see at once that a notable hiatus in deposition, and therefore in geological chronology, must exist between the older conformable series, *a b c*, and the later strata by which these are covered. The former had been deposited, folded, upheaved, and worn down before the accumulation of the newer series upon their denuded edges. These changes must have demanded a considerable lapse of time. Yet, looking merely at the structure in itself, we have evidently no means of fixing, even relatively, the length of interval marked by an unconformability. By ascertaining, from some other region, the full suite of formations, we learn what members of the succession are wanting. In this way, it would be discovered that the greater part of the Carboniferous system, the whole of the Permian, and the Trias and the Lias are absent from the ground represented in Fig. 323 (compare Fig. 221). The mere violence of contrast between a set of vertical beds below and a horizontal group above, is in itself no certainly reliable criterion of the relative lapse of time between their deposition; for obviously, an older portion of a given formation might be tilted on end, and be overlain unconformably by a later part of the same formation. A set of flat rocks of high geological antiquity may, on the other hand, be conformably covered by a formation of comparatively recent date, yet, in spite of the want of discordance between the two, they might have been separated by a large portion of the total sum of geological time. Further examination will usually suffice to show that the conformability in such cases is only partial or accidental, and that localities may be found where the formations are distinctly unconformable. From the centre of the section in Fig. 324, for example, the two groups of rocks might, on casual examination, be pronounced to be conformable. Yet at short distances on either side, proofs of violent unconformability are conspicuous. It sometimes happens that more than one unconformability may

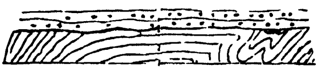

Fig 324.—Section of local deceptive Conformability

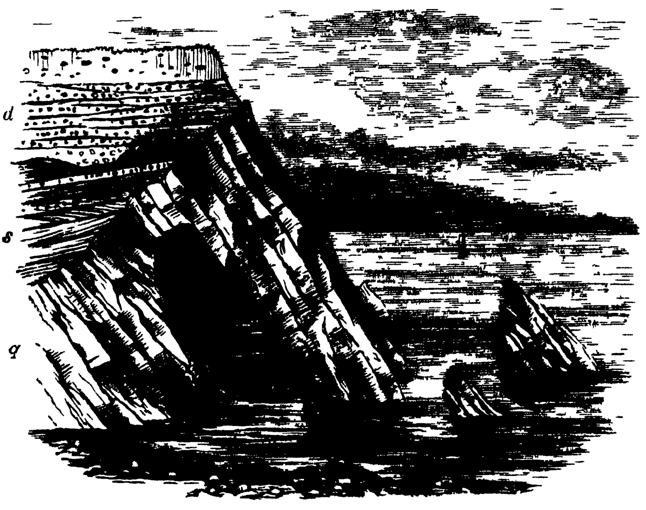

Fig 325.—Double Unconformability at Cullen, Banffshire.
q, Quartzite, s, Old Red Sandstone, d, Post-Tertiary Gravels

be detected in the same section. Thus in Fig. 325, the break between the quartzite (*q*) and Old Red Sandstone (*s*) is to the eye much more violent and complete than that between the sandstone and the overlying gravels and clays (*d*). Yet the interval separating the epoch of the quartzite from that of the sandstone may have been brief, when compared with the vast lapse of time that intervened between the nearly flat sandstones and overlying superficial deposits. It is by the evidence of organic remains that the relative importance of unconformabilities must be measured, as will be explained in Book V.

Paramount though the effect of an unconformability may be in the geological structure of a country, it must nevertheless, when viewed on the large scale, be merely local. The disturbance by which it was produced will usually be found to have affected a comparatively circumscribed region, beyond the limits of which the continuity of sedimentation may have been undisturbed. We may, therefore, generally expect to be able to fill up the gaps in one district or country from the more complete geological formations of another.

BOOK V.

PALÆONTOLOGICAL GEOLOGY.

PALÆONTOLOGY treats of the structure, affinities, classification, and distribution in time of the forms of plant and animal life imbedded in the rocks of the earth's crust. Considered from the biological side, it is a part of zoology and botany. A proper knowledge of extinct organisms can only be attained by the study of living forms, while our acquaintance with the history and structure of modern organisms is amplified by the investigation of their extinct progenitors. Viewed, on the other hand, from the physical side, palæontology is a branch of geology. It is mainly in this latter aspect that it will here be discussed.

Palæontology or Palæontological Geology deals with fossils or organic remains preserved in natural deposits, and endeavours to gather from them information as to the history of the globe and its inhabitants. The term fossil, meaning literally anything "dug up," was formerly applied indiscriminately to any mineral substance taken out of the earth's crust, whether organised or not. Ordinary minerals and rocks were thus included as fossils. For many years, however, the meaning of the word has been so restricted as to include only the remains or traces of plants and animals preserved in any natural formation, whether hard rock or loose superficial deposit. The idea of antiquity or relative date is not necessarily involved in this conception of the term. Thus, the bones of a sheep buried under gravel and silt by a modern flood, and the obscure crystalline traces of a coral in ancient masses of limestone, are equally fossils.[1] Nor has the term fossil any limitation as to organic grade. It includes not merely the remains of organisms, but also whatever was directly connected with or produced by these organisms. Thus, the resin which exuded from trees of long-perished forests is as much a fossil as any portion of the stem, leaves, flowers, or fruit, and in some respects, is even more valuable to the geologist than more determinable remains of its parent trees, because it has often preserved in admirable perfection the insects which flitted about in the woodlands. The burrows or trails of a worm, in sandstone or shale, claim recognition as fossils, and indeed are commonly the only indications to be met with of the existence of annelide life among old geological formations. The droppings (coprolites) of fishes and reptiles are excellent fossils, and tell their tale as to the presence and food of vertebrate life in ancient waters. The little agglutinated cases of the caddis-worm remain as fossils in formations from which perchance most other traces of life may have passed away. Nay, the very handiwork of man, when preserved in any natural manner is entitled to rank among fossils; as where his flint-implements have been dropped into the prehistoric gravels of river-valleys, or where his canoes have been buried in the silt of lake-bottoms.

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[1] The word "fossil" is sometimes wrongly used as synonymous with "petrified," and we accordingly find the intolerable barbarism of "sub-fossil."

The term fossil, moreover, suffers no restriction as to the condition or state of preservation of any organism. In some rare instances, the very flesh, skin, and hair of a mammal have been preserved for thousands of years, as in the case of mammoth carcases entombed in the frozen mud-cliffs of Siberia.[1] Generally, all or most of the original animal matter has disappeared, and the organism has been more or less completely mineralized or petrified. It often happens that the whole organism has decayed, and a mere cast in amorphous mineral matter, as sand, clay, ironstone, silica, or limestone, remains; yet all these variations must be comprised in the comprehensive term fossil.

Two preliminary questions demand attention: in the first place, how remains of plants and animals come to be entombed in rocks, and in the second, how they have been preserved there so as to be now recognisable.

§ **1. Conditions for the entombment of organic remains.**—If what takes place at the present day may fairly be taken as an indication of what has been the ordinary condition of things in the geological past, there must have been so many chances against the conservation of either animal or plant remains, that their occurrence among stratified formations should be regarded as exceptional, and as the result of various fortunate accidents.

1. On Land.—Let us consider, in the first place, what chances exist for the preservation of remains of the present fauna and flora of a country. The surface of the land may be densely clothed with forest, and abundantly peopled with animal life. But the trees die and moulder into soil. The animals, too, disappear, generation after generation, and leave few perceptible traces of their existence. If we were not aware from authentic records that central and northern Europe was covered with vast forests at the beginning of our era, how could we know this fact? What has become of the herds of wild oxen, the bears, wolves, and other denizens of the lowlands of primeval Europe? For unknown ages, too, the North American prairies have been roamed over by countless herds of buffaloes, yet, except here and there a skull and bones of some comparatively recent individual, every trace of these animals has disappeared from the surface.[2] How could we prove from the examination of the

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[1] For particulars of a recent exhumation see 'Beitrage zur Kenntniss des Russischen Reiches,' Bd. III. (1887) p. 175.

[2] See Jules Marcou, 'Lettres sur les roches du Jura,' p. 103.

soil either in Europe or North America that such creatures, though now locally extinct, had once abounded there? We might search in vain for any superficial relics of them, and should learn by so doing that the law of nature is everywhere "dust to dust."

The conditions for the preservation of evidence of terrestrial (including freshwater) plant and animal life must, therefore, be always local, and, so to say, exceptional. They are supplied only where organic remains can be protected from air and superficial decay. Hence, they may be observed in lakes, peat-mosses, deltas at river-mouths, caverns, deposits of mineral-springs and volcanoes.

a. Lakes.—Over the floor of a lake, deposits of silt, peat, marl, &c., are formed. Into these, the trunks, branches, leaves, flowers, fruits, or seeds of plants from the neighbouring land may be carried, together with the bodies of vertebrates, birds, and insects. An occasional storm may blow the lighter débris of the woodlands into the water. Such portions of the wreck as are not washed ashore again, may sink to the bottom, where they will, for the most part, probably rot away, so that, in the end, only a very small fraction of the whole vegetable matter, cast over the lake by the wind, is covered up and preserved at the bottom. In like manner, the remains of winged and four-footed animals, swept by winds or by river-floods into the lake, run so many risks of dissolution, that only a proportion of them, and probably merely a small proportion, is preserved. When we consider these chances against the conservation of the vegetable and animal life of the land, we must admit that, at the best, lake-bottoms can contain but a meagre and imperfect representation of the abundant life of the adjacent hills and plains. Lakes, however, have a distinct flora and fauna of their own. Their aquatic plants may be entombed in the gathering deposits of the bottom. Their mollusks, of characteristic types, sometimes form, by the accumulation of their remains, sheets of soft calcareous marl (pp. 139, 484), in which many of the undecayed shells are preserved. Their lacustrine fishes, likewise, must no doubt often be entombed in the silt or marl.

b. Peat-mosses.—Wild animals, venturing on the more treacherous watery parts of peat-bogs, are sometimes engulphed or "laired." The antiseptic qualities of the peat preserve their remains from decay. Hence, from European peat-mosses, numerous remains of deer and oxen have been exhumed. Evidently the larger beasts of the forest ought chiefly to be looked for in these localities (p. 478).

c. Deltas at river-mouths.—It is obvious that, to some extent, both the flora and the fauna of the land may be buried among the sand and silt of deltas (p. 401). But though occasional or frequent river-floods sweep down trees, herbage, and the bodies of land-animals, the carcases so transported run every risk of having their bones separated and dispersed,[1] or of decaying or being otherwise destroyed, while still afloat; and even if they reach the bottom, they tend to dissolution there, unless speedily covered up and protected by fresh sediment. Delta-formations can therefore scarcely be expected to preserve more than a meagre outline of a varied terrestrial flora and fauna.

d. Caverns.—These are eminently adapted for the preservation of the higher forms of terrestrial life (pp. 368, 494). Most of our knowledge of the prehistoric mammalian fauna of Europe is derived from what has been disinterred from *bone-caves*. As these recesses lie, for the most part, in limestone or in calcareous rock, their floors are commonly coated with stalagmite from the drip of the roof; and as this deposit is of great closeness and durability, it has effectually preserved whatever it has covered or enveloped. The caves have, in many instances, served as dens for predatory beasts, like the hyæna, cave-lion, and cave-bear, which sometimes dragged their prey into these recesses. In other cases, they have been merely holes whither different animals crawled to die, or into which they fell or were swept by inundations. Under whatever circumstances the animals left their remains in these subterranean retreats, the bones have been covered up and preserved. Still we must admit that, after all, only a small fraction of the animals of the time would enter the caves, and therefore that the evidence of the cavern-deposits, profoundly interesting and valuable as it is, presents us with merely a glimpse of one aspect of the life of the land.

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[1] Lower jaws, for instance, because they are among the earliest parts of the skeleton of a floating carcase to drop off are not infrequently met with as fossils.

e. Deposits of mineral-springs.—The deposits of mineral matter, resulting from the evaporation of mineral springs on the surface of the ground, serve as receptacles for occasional leaves, land-shells, insects, dead birds, small mammals, and other remains of the plant and animal life of the land (pp. 366, 482).

f. Volcanic deposits.—Sheets of lava and showers of volcanic dust may entomb terrestrial organisms (pp. 201, 594). It is obvious, however, that even over the areas wherein volcanoes occur and continue active, they can only to a very limited extent entomb and preserve the flora and fauna of the land.

2. In the Sea.—In the next place, if we turn to the sea, we find certainly more favourable conditions for the preservation of organic forms, but also many circumstances which operate against it.

a. Littoral deposits.—While the level of the land remains stationary, there can be but little effective entombment of marine organisms in littoral deposits; for only a limited accumulation of sediment will be formed until subsidence of the sea-floor takes place. In the trifling beds of sand or gravel thrown up by storms above the limits of ordinary wave-action on a stationary shore, only the harder and more durable forms of life, such as the stronger gasteropods and lamellibranchs, which can withstand the triturating effects of the beach-waves, are likely to remain uneffaced (p. 454).

b. Deeper-water terrigenous deposits.—Below tide-marks, along the margin of land whence sediment is derived, conditions are more favourable for the preservation of marine organisms. Sheets of sand and mud are there laid down, wherein the harder parts of many forms of life may be entombed and protected from decay (p. 455). But probably only a small proportion of the fauna that crowds these marginal waters of the ocean, with perhaps an occasional pelagic species, may be expected to occur in such deposits. Moreover, for the entombment and preservation of the remains of these organisms, there must obviously be a sufficiently abundant and rapid deposit of sediment, combined with a slow depression of the sea-bottom. Under the most favourable conditions, therefore, the organic remains actually preserved will usually represent little more than a mere fraction of the whole assemblage of life in these juxta-terrestrial parts of the ocean.

c. Abysmal deposits.—In proportion to distance from land, the rate of deposition of sediment on the sea-floor must become feebler, until in the remote central abysses it reaches a hardly appreciable minimum, while at the same time, the solution of calcareous organisms may become marked in deep water (p. 457). Except, therefore, where organic deposits such as ooze, are forming in these more pelagic regions, the conditions must be on the whole unfavourable for the preservation of any adequate representation of the deep-sea fauna. Hard enduring objects, such as teeth and bones, may slowly accumulate and be protected by a coating of peroxide of manganese, or of silicates, such as are now forming here and there over the deep sea-bottom. Yet a deposit of this nature, if raised into land, would supply but a meagre picture of the life of the sea.

In considering the various conditions under which marine organisms may be entombed and preserved, we must take into account certain occasional phenomena, when sudden, or at least rapid and extensive, destruction of the fauna of the sea may be caused. (1) Earthquake shocks have been followed by the washing ashore of vast quantities of dead fish.[1] (2) Violent storms, by driving shoals of fishes into shallow water and against rocks, produce enormous destruction. Dr. Leith Adams describes the coast of part of the Bay of Fundy as being covered to a depth of a foot in some places with dead fish, dashed ashore by a storm on the 24th of September, 1867.[1] (3) Copious discharges of fresh water into the sea have been observed to cause extensive mortality among marine organisms. Thus, during the S.W. monsoon and accompanying heavy rains, the west coasts of some parts of India are covered with dead fish thrown ashore from the sea.[2] (4) A sudden irruption of the outer sea into a sheltered and partially brackish inlet may cause the extinction of many of the denizens of the latter, though a few may be able to survive the altered conditions.[3] (5) Volcanic explosions have been observed to cause considerable destruction to marine life, either from the heat of the lava, or from the abundance of ashes or of poisonous gases. (6) Want of oxygen, when fishes are crowded together in frightened shoals, or when, burrowing in sand and mud, they are overwhelmed with rapidly accumulating detritus, is another cause of mortality.[4] (7) Shoals of fish are sometimes driven ashore by the large predatory denizens of the deep, such as whales and porpoises. (8) Too much or too little heat in shallow water leads to the destruction of fish. Large numbers of salmon are sometimes killed in the pools of a river during dry and hot weather. (9) Considerable mortality occasionally arises along the littoral zone from the effects of severe frost. (10) Various diseases and parasites affect fish, and lead directly to their death, or weaken them so that they are more easily caught by their enemies.[5] Such phenomena suggest probable causes of death in the case of fossil fishes, whose remains are sometimes crowded together in various geological formations, as for example, in the Old Red Sandstone.

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[1] C. Forbes *Q. J. Geol. Soc.* xiv. '1858) p. 294.

Of the whole sea-floor, the area best adapted for preserving organic exuviæ is obviously that belt in which life is most varied and abundant, and where, along the margin of the land, fresh layers of sediment, transported by rivers and currents from the adjacent shores, are laid down. The most favourable conditions for the accumulation of a thick mass of marine fossiliferous strata will arise when the area of deposit is undergoing a gradual subsidence. If the rate of depression and that of deposit be equal, or nearly so, the movement may conceivably continue for a vast period without producing any great apparent change in marine geography, and even without seriously affecting the distribution of life over the sea-floor within the area of subsidence. Hundreds or thousands of feet of sedimentary strata may conceivably be in this way heaped up round the continents, containing a fragmentary series of remains, chiefly forms of shallow-water life which had hard parts capable of preservation.

There can be little doubt that such has, in fact, been the history of the main mass of stratified formations in the earth's crust. These piles of marine strata have unquestionably been laid down for the most part in comparatively shallow water, within the area of deposit of terrestrial sediment. Their great depth seems only explicable by prolonged and repeated movements of subsidence, sometimes interrupted, however, as we know, by other movements of a contrary kind. These geographical changes affected at once the deposition of inorganic materials and the succession of organic forms. One series of strata is sometimes abruptly succeeded by another of a very different character, and we not uncommonly find a corresponding contrast between their respective organic contents.

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[1] *Q. J. Geol. Soc.* xxix. p. 303.

[2] Denison, *op. cit.* xviii. p. 453. *Nature* (December 19, 1872, p. 124) gives another instance.

[3] Forchhammer, *Edin. New. Phil. Journ.* xxxi. p. 69. *Nature*, i. p. 454 ; xiii. p. 107.

[4] Sir J. W. Dawson, *Geologist*, ii. (1859) p. 216.

[5] For fuller references, see an interesting paper by Prof. T. Rupert Jones, *Geol. Mag.* 1882 p. 533.

It follows, from these conditions of sedimentation, that representatives of the abysmal deposits of the central oceans are not likely to be met with among the geological formations of past times. Thanks to the great work done by the *Challenger* Expedition, we know what are the leading characters of the accumulations now forming on the deeper parts of the ocean-floor. So far as we yet know, they have no analogues among the formations of the earth's crust. They differ, indeed, so entirely from any formation which geologists have considered to be of deep-water origin as to indicate that, from early geological times, the present great areas of land and sea have remained on the whole where they are, and that the land consists mainly of strata formed of terrestrial débris laid down at successive epochs in the surrounding comparatively shallow seas.

§ ii. **Preservation of organic remains in mineral masses.**—The condition of the remains of plants and animals in rock-formations depends, first, upon the original structure and composition of the organisms, and secondly, upon the manner in which their "fossilization" that is, their entombment and preservation, has been effected.

1. Influence of original structure and composition.—The durability of organisms is determined by their composition and structure.

The internal skeletons of most vertebrate animals consist mainly of phosphate of lime; in saurians and fishes, there is also an exo-skeleton of hard bony plates or of scales. It is these durable portions that remain as evidence of the former existence of vertebrate life. The hard parts of invertebrates present a greater variety of composition. In the vast majority of cases, they consist of calcareous matter, either calcite or aragonite. The carbonate of lime is occasionally strengthened by phosphate, while in a few cases, as in the horny brachiopods, in *Conularia*, *Serpula*, and some other forms, the phosphate is the chief constituent.[1] Next in abundance to lime is silica, which constitutes the frustules of diatoms and the harder parts of many protozoa, and is found also in the teeth of some mollusks. The integuments of insects, the carapaces of crustacea, and some other organisms, are composed fundamentally of chitin,[2] a transparent horny substance which can long resist decomposition. In the vegetable kingdom, the substance known as cellulose forms the essential part of the framework of plants. In dry air, it possesses considerable durability, also when thoroughly water-logged and excluded from meteoric influences. In the latter condition imbedded amid mud or sand, it may last until gradually petrified.[3]

It is a familiar fact that in the same stratum different organisms occur in remarkably different states of conservation. This is sometimes strikingly exemplified among the mollusca. The conditions for their preservation may have been the same, yet some kinds of shells are found only as empty moulds or casts, while others still retain their form, composition, and structure. This discrepancy, no doubt, points to original differences of composition or structure. The aragonite shells of a stratum may be entirely dissolved, while those of calcite may remain.[1] The presence, therefore, of calcite forms only does not necessarily imply that others of aragonite were not originally present. But the conditions of petrifaction have likewise greatly varied. In the clays of the Mesozoic formations, for example, cephalopods may be exhumed retaining even their pearly nacre, while in corresponding deposits among the Palæozoic systems they are merely crystalline calcite casts.

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[1] Logan and Hunt, *Amer. Journ. Sci.* xvii. (1854) p. 235.

[2] According to C. Schmidt, the composition of this substance is C, 46·64; H, 6·60; N, 6·66; O, 40·20. The brown chitin of Scottish Carboniferous scorpions is hardly distinguishable from that of recent species.

[3] On cellulose and coal, see C. F. Cross and E. J. Bevan, *Brit. Assoc.* 1881, Sects. p. 603.

2. Fossilization.—The condition in which organic remains have been entombed and mineralized may be reduced to three leading types.

(1) *The original substance is partly or wholly preserved.*—Several grades may be noticed: (*a*) where the entire animal substance is retained, as in the frozen carcases of mammoths in the Siberian cliffs; (*b*) where the organism has been mummified by being encased in resin or gum (insects in amber); (*c*) where the organism has been carbonized with or without retention of its structure, as is characteristically shown in peat, lignite, and coal; (*d*) where a variable portion of the original substance, and especially the organic matter, has been removed, as happens with shells and bones: this is no doubt one of the first steps towards petrifaction.

(2) *The original substance is entirely removed, with retention merely of external form.*—Mineral matter gathers round the organism and hardens there, while the organism itself decays. Eventually a mere mould of the plant or animal is left in stone. Every stage in this process may be studied along the margin of calcareous springs and streams (*ante*, p. 482). The lime in solution is precipitated round fibres of moss, leaves, twigs, &c., which are thereby incrusted with mineral matter. While the crust thickens, the organism inside decays, until a mere hollow mould of its form remains. Among stratified rocks, moulds of organic forms are of frequent occurrence. They may be filled up with mineral matter, washed in mechanically or deposited as a chemical precipitate, so that a cast in stone replaces the original organism. Such casts are particularly common in sandstone, which, being a porous rock, has allowed water to filter through it and remove the substance of enclosed plant-stems, shells, &c. In the sandstones of the Carboniferous system, casts in compacted sand of stems of *Lepidodendron* and other plants are abundant. It is obvious that in casts of this kind, no trace remains of the original structure of the organism, but merely of its external form.

(3) *The original substance is molecularly replaced by mineral matter with partial or entire preservation of the internal structure of the organism.*—This is the only true petrifaction. The process consists in the abstraction of the organic substances, molecule by molecule, and in their replacement by precipitated mineral matter. So gradual and thorough has this interchange often been, that the minutest structures of plant and animal have been perfectly preserved. Silicified wood is a familiar example (see p. 364).

The chief substance which has replaced organic forms in rocks is calcite, either crystalline or in an amorphous granular condition. In assuming a crystalline (or fibrous) form, this mineral has often observed a symmetrical grouping of its component individuals, these being usually placed with their long axes perpendicular to the surface of an organism. In many cases, among invertebrate remains, the calcite now visible is pseudomorphous after aragonite (p. 122). Next in abundance as a petrifying medium is silica, most commonly in the chalcedonic form, but also as quartz. It is specially frequent in some limestones, as chert and flint, replacing the carbonate of lime in mollusks, echinoderms, corals, &c. It also occurs in irregular aggregates, in which organisms are sometimes beautifully preserved. It forms a frequent material for the petrifaction of fossil wood. Silicification, or the replacement of organisms by silica, is the process by which minute organic structures have been most perfectly preserved. In a microscopic section of silicified wood, the organisation of the original plant may be as distinct as in the section of any modern tree. Pyrites and marcasite, especially the latter, are common replacing minerals, abundant in argillaceous deposits, as, for example, among the Jurassic and Cretaceous clays. Siderite has played a similar part among the ironstones of the Coal-measures, where shells and plants have been replaced by it. Many other minerals are occasionally found to have been substituted for the original substance of organic remains. Among these may be mentioned glauconite (replacing or filling foraminifera), vivianite (specially frequent as a coating on the weathered surface of scales and bones), barytes, celestine, gypsum, talc, lead-sulphate, carbonate, and sulphide; copper-sulphide and native copper; hæmatite and limonite; zinc-carbonate and sulphide; cinnabar; silver chloride and native silver; sulphur, fluorite, phosphorite.[1]

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[1] See *ante*, pp. 122, 138, and authorities there cited.

§ iii. **Relative Palæontological value of organic remains.**—As the conditions for the preservation of organic remains exist more favourably under the sea than on land, relics of marine must be far more abundantly conserved than those of terrestrial organisms. This is true to-day, and has doubtless been true in all past geological time. Hence, for the purposes of the geologist, fossil remains of marine forms of life far surpass all others in value. Among them, there will necessarily be gradations in importance, regulated chiefly by their possession of hard parts, readily susceptible of preservation among marine deposits. Among the Protozoa, foraminifers, radiolarians, and sponges, possessing siliceous or calcareous organisations, have been preserved in deposits of all ages. Of the Cœlenterates, those which, like the corals, secrete a calcareous skeleton are important rock-builders. The Echinoderms have been so abundantly preserved that their geological history and development are better known than those of most other classes of invertebrates. The Annelides, on the other hand (except where they have been tubicolar), have almost entirely disappeared, though their former presence is often revealed by the trails they have left upon surfaces of sand and mud. Of all the marine tribes which live within the juxta-terrestrial belt of sedimentation, unquestionably the Mollusca stand in the front rank, as regards their aptitude for becoming fossils. In the first place, they almost all possess a hard durable shell, composed chiefly of mineral matter, capable of resisting considerable abrasion, and readily passing into a mineralized condition. In the next place, they are extremely abundant both as to individuals and genera. They occur on the shore up to high-water mark, and range thence down into the abysses. Moreover, they appear to have possessed these qualifications from early geological times. In the marine Mollusca, therefore, we have a common ground of comparison between the stratified formations of different periods. They have been styled the alphabet of palæontological inquiry. It will be seen, as we proceed, how much, in the interpretation of geological history, depends upon the testimony of sea-shells.

Turning next to the organisms of the land, we perceive that the abundant terrestrial flora has a comparatively small chance of being well represented in a fossil state; that indeed, as a rule, only that portion of it of which the leaves, twigs, flowers, fruits, or trunks are blown into lakes, or swept down by rivers, is likely to be partially preserved. Terrestrial plants, therefore, occur in comparative rarity among stratified rocks, and furnish in consequence only limited means of comparison between the formations of different ages and countries (see pp. 660, 668). Of land animals, the vast majority perish, and leave no permanent trace of their existence. Predatory and other forms, whose remains may be looked for in caverns or peat-mosses, must occur more numerously in the fossil state than birds, and are correspondingly more valuable to the geologist for the comparison of different strata.

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[1] Roth, 'Chem. Geol.' i. p. 605. Jannettaz, *Bull. Soc. Géol. France* (3), vii. p. 102.

Another character determines the relative importance of fossils as geological monuments. All organisms have not the same inherent capability of persistence. The longevity of an organic type has, on the whole, been in inverse proportion to its perfection. The more complex its structure, the more susceptible has it been of change, and consequently the less likely to be able to withstand the influences of changing climate, and other physical conditions. A living species of foraminifer or brachiopod, endowed with comparative indifference to its environment, may spread over a vast area of the sea-floor, and the same want of sensibility enables it to endure through the changing physical conditions of successive geological periods. It may thus possess a great range, both in space and time. But a highly-specialised mammal is usually confined to but a limited extent of country, and to a narrow chronological range.[1]

§ **iv. Uses of Fossils in Geology.**—Apart from their profound interest as records of the progress of organised being upon the earth, fossils serve two main purposes in geological research: (1) to throw light upon former conditions of physical geography, such as the presence of land, rivers, lakes, and seas, in places where they do not now exist, upon changes of climate, and upon the former distribution of plants and animals; and (2) to furnish a guide in geological chronology whereby rocks may be classified according to relative date, and the facts of geological history may be arranged and interpreted as a connected record of the earth's progress.

1. Changes in Physical Geography.—A few examples will suffice to show the manifold assistance which fossils furnish to the geologist in the elucidation of ancient geography.

(*a*) Former land-surfaces are revealed by the presence of tree-stumps in their positions of growth, with their roots branching freely in the underlying stratum, which, representing the ancient soil, often contains leaves, fruits, and other sylvan remains, together with traces of the bones of land animals, remains of insects, land-shells, &c.

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[1] The great value of mammalian remains for purposes of geological chronology has been well enforced by Prof. Marsh. See especially his address to the American Association for the Advancement of Science, 30th August 1877, and a subsequent paper in *Amer. Journ. Sci.* xlii. (1891) p. 336. Mr. W. T. Blanford points out that, in some cases at least, fluviatile mollusks have been more short-lived than terrestrial mammals. *Address, Geol. Section, Brit. Assoc.* 1884.

Ancient woodland surfaces of this kind, found between tide-marks, and even below low-water line, round different parts of the British coast, unequivocally prove a subsidence of the land ('Submerged Forests,' p. 289). Of more ancient date are the "dirt-beds" of Portland (Book VI. Part III. Section ii. § 2), which, by their layers of soil and tree-stumps, show that woodlands of cycads sprang up over an upraised sea-bottom and were buried beneath the silt of a river or lake. Still further back in geological history come the coal-growths of the Carboniferous period, which, with their "under-clays" or soils, point to wide jungles of terrestrial or aquatic plants, like the modern mangrove-swamps that were successively submerged and covered with sand or silt (Book VI. Part II. Sect. iv. § 1).

(*b*) The former existence of lakes can be satisfactorily proved from beds of marl or lacustrine limestone full of freshwater shells, or from fine silt with leaves, fruits, and insect remains. Such deposits are growing abundantly at the present day, and they occur at various horizons among the geological formations of past times. The well-known Nagelflue of Switzerland—a mass of conglomerate attaining a thickness of more than 1000 feet—can be shown from its fossil contents to be essentially a lacustrine deposit (Book VI. Part IV. Sect. ii. § 2). Still more important are the ancient Eocene and Miocene lake-formations of North America, whence so rich a terrestrial and lacustrine flora and fauna have been obtained (Book VI. Part. IV. Sect. i. § 1).

(*c*) Old sea-bottoms are vividly brought before us by beds of marine shells and other organisms. Layers of water-worn gravel and sand, with rolled shells of littoral and infra-littoral species, unmistakably mark the position of a former shore-line. Deeper water is indicated by finer muddy sediment, with relics of the fauna that prevails beneath the reach of waves and ground-swell. Limestones full of corals, or made up of crinoids, point to the slow, continuous growth and decay of generation after generation of organisms in clear sea-water.

(*d*) Variations in the nature of the water, or of the sea-bottom, may sometimes be shown by changes in the size or shape of the organic remains. If, for example, the fossils in the central and lower parts of a limestone are large and well-formed, but in the upper layers become dwarfed and distorted, we may reasonably infer that the conditions for their continued existence at the locality must have been gradually impaired. The final complete cessation of these favourable conditions is shown by the replacement of limestone by shale, indicative of the water having become muddy, and by the disappearance of the organisms, which had shown their sensitiveness to the change.

(*e*) The proximity of land at the time when a fossiliferous stratum was in the course of accumulation may be sufficiently proved by mere lithological characters, as has been already explained; but the conclusion may be further strengthened by the occurrence of leaves, stems, and other fragments of terrestrial vegetation, with remains of insects, birds, or terrestrial mammals, which, if found in some numbers in certain strata intercalated among others containing marine organisms, would make it improbable that they had been drifted far from land (see p. 456).

f) The existence of different conditions of climate in former geological periods is satisfactorily demonstrated from the testimony of fossils. Thus, an assemblage of the remains of palms, gourds, and melons, with bones of crocodiles, turtles, and sea-snakes, proves a sub-tropical climate to have prevailed over the south of England in the older Tertiary ages (Book VI. Part IV. Sect. i. § 1). On the other hand, the extension of a cold or arctic climate far south into Europe during post-Tertiary time, can be shown from the existence of remains of arctic animals, even in the south of England and of France (Book VI. Part V.) This is a use of fossils, however, where great caution must be observed. We cannot affirm that, because a certain species of a genus lives now in a warm part of the globe, every species of that genus must always have lived in similar circumstances. The well-known examples of the mammoth and woolly rhinoceros that lived in the cold north, while their modern representatives inhabit some of the warmest regions of the globe, may be usefully remembered as a warning against any such conclusion. When, however, not one fossil merely, but the whole assemblage of fossils in a group of rocks, finds its modern analogy in a certain general condition of climate, we may, at least tentatively, infer that the same kind of climate prevailed where that assemblage lived. Such an inference would become more and more unsafe in proportion to the antiquity of the fossils, and their divergence from existing forms.[1]

As an illustration of this application of the evidence of fossils in the interpretation of ancient conditions of geography at different geological periods, reference may be made more especially to the investigation of the various basins in which the Jurassic rocks of Europe were deposited. The positions of the seas and lands, and the variations of climate have been ascertained with sufficient definiteness to give us some conception of the physical geography of that part of the globe during early Mesozoic time.[2]

2. Geological Chronology.—Although absolute dates cannot be fixed in geological chronology, it is not difficult to determine the relative age of different strata. For this purpose the fundamental law is based on the "order of superposition" (pp. 523, 674): in a series of stratified formations, the older underlie the younger. It is not needful that we should actually see the one lying below the other. If a continuous conformable succession of strata dips steadily in one direction, we know that the beds at the one end must underlie those at the other, because we can trace the whole succession of beds between them. Rare instances occur, where strata have been so folded by great terrestrial disturbance that the younger are made to underlie the older. But this inversion can usually be made clear from other evidence. The true order of superposition is decisive of the relative ages of stratified rocks.

The order of sequence having been determined, it is needful to find some means of indentifying a particular formation elsewhere, when its stratigraphical relations may possibly not be visible. At first, it might be thought that the mere external aspect and mineral characters of the rocks ought to be sufficient for this purpose. Undoubtedly these features may suffice within the same limited region in which the order of sequence has already been determined. But as we recede from that region, they become more and more unreliable. That this must be the case will readily appear, if we reflect upon the conditions under which sedimentary accumulations have been formed. The markedly lenticular nature of these deposits has already been described (p. 515). At the present day, the sea-bottom presents here a bank of gravel, there a sheet of sand, elsewhere layers of mud, or of shells, or of organic ooze, all of which are in course of deposit simultaneously, and will as a rule be found to shade off laterally into each other. The same diversity of contemporaneous deposits has obtained from the earliest geological periods. Conglomerates, sandstones, shales, and limestones occur on all geological horizons, and replace each other even on the same platform. The Coal-measures of Pennsylvania are represented west of the Rocky Mountains by thousands of feet of massive marine limestones. The white Chalk of England lies on the same geological horizon with marls and clays in North Germany, with thick sandstones in Saxony, with hard limestone in the south of France. Mere mineral characters are thus quite unreliable, save within comparatively restricted areas.

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[1] See Neumayr, *Nature*, xlii. (1890) pp. 148, 175. This author specially devoted himself to the study of ancient climates as indicated by fossils. As an illustration of his methods consult his essay on the climatic zones of Jurassic and Cretaceous time, *Denksch. Akad. Wien*, xlvii. (1883); also the same work, vol. l. (1885). "Fossil plants as tests of Climate"—the Sedgwick Prize Essay for 1892. By A. C. Seward. Cambridge, C. J. Clay, 1892.

[2] See especially Neumayr, *Verh. Geol. Reichsanst.* 1871, p. 54, *Jahrb. Geol. Reichsanst.* xxviii. (1878), and his essay cited in the foregoing note.

The solution of this problem was found, and was worked out for the Secondary rocks of England, by William Smith at the end of last century. It is supplied by organic remains, and depends upon the law that the order of succession of plants and animals has been similar all over the world. According to the order of superposition, the fossils found in any deposit must be older than those in the deposit above, and younger than those in that below. This order, however, must be first accurately determined by a study of the actual stratigraphy of the formations; for, so far as regards organic structure or affinities, there may be no discoverable reason why a particular species should precede or follow another. Unless, for example, we knew from observation that *Rhynchonella pleurodon* is a shell of the Carboniferous Limestone, and *Rhynchonella tetrahedra* is a shell of the Lias, we could not, from mere inspection of the fossils themselves, pronounce as to their real geological position.[1] It is quite true that, by practice, a palæontologist has his eye so trained that he can make shrewd approximations to the actual horizon of fossils which he may never have seen before (and this is more especially true in regard to the mammalia, as will be immediately adverted to), but he can only do this by availing himself of a wide experience, based upon the ascertained order of appearance of fossils, as determined by the law of superposition. For geological purposes, therefore, and, indeed, for all purposes of comparison between the faunas and floras of different periods, it is absolutely essential, first of all, to have the order of superposition of strata rigorously determined. Unless this is done, the most fatal mistakes may be made in palæontological chronology. But when it has once been done in one typical district, the order thus established may be held as proved for a wide region where, from paucity of sections, or from geological disturbance, the true succession of formations cannot be satisfactorily determined.

The order of superposition having been determined in a great series of stratified formations, it is found that the fossils at the bottom are not quite the same as those at the top of the series. As we trace the formations upward, we discover that species after species of the lowest platforms disappears, until perhaps not one of them is found. With the cessation of these older species, others make their entrance. These, in turn, are found to die out and to be replaced by newer forms. After patient examination of the rocks, it is ascertained that every well-marked formation is characterised by its own species or genera (type-fossils, Leitfossilien) or by a general assemblage or *facies* of organic forms. This can only, of course, be determined by actual practical experience over an area of some size. The characteristic fossils are not always the most numerous; they are those which occur most constantly and have not been observed to extend their range above or below a definite geological horizon or platform. For the determination of geological chronology, as already pointed out, it may be affirmed as a general principle that the higher and more specialised the type of organism the more local is its area in space and the more limited its range in time. Hence mammalian remains have a special value in this respect.[1] But some invertebrate groups possess great importance as fixing stratigraphical horizons; as for example the ammonites in the Jurassic and the graptolites in the Silurian system.

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[1] The derivation of some forms by descent from others may be inferred with more or less probability, and such genetic affinities may furnish valuable suggestions to the palæontologist. But that the risk of erroneous interpretation and fanciful deduction in such matters is real and serious was well shown in the discussion of the presumed derivation of the Olenellidian trilobites from the Paradoxidian forms, until it was shown that the former were really the precursors of the latter.

As illustrations of type-fossils characteristic of some of the larger subdivisions of the Geological Record, the following may be given. Lepidodendra and Sigillaria are typical of Old Red Sandstone and Carboniferous deposits; Graptolites of the Silurian system; Trilobites of Palæozoic rocks from Cambrian to Carboniferous, Cystideans of the older Palæozoic rock-groups. Orthoceratites are Palæozoic, and Ammonites are Mesozoic; Ichthyosaurs and Plesiosaurs, Mesozoic; Nummulites, Palæotherium, Anoplotherium, Hyopotamus, and Anthracotherium belong to older Tertiary, and Mastodon, Elephas, Hyæna, Cervus, and Equus to younger Tertiary and recent time. The occurrence of such organisms in any rock, at once indicates the great division of geological time to which the rock should be assigned.

The type-fossils of a system or formation, having been ascertained from a sufficiently prolonged and extended experience, serve to identify that series of rocks in its progress across a country. Thus, as we trace a formation into tracts where it would be impossible to determine the true order of superposition, owing to the want of sections, or to the disturbed condition of the rocks, we can employ the type-fossils as a means of identification, and speak with confidence as to the succession of the rocks. We may even demonstrate that in some mountainous ground, the strata have been turned completely upside down, if we can show that the fossils in what are now the uppermost layers ought properly to lie underneath those in the beds below them.

Prolonged study of the succession of organic types in the geological past all over the world, has given palæontologists some confidence in fixing the relative age of fossils belonging even to previously unknown species or genera, and occurring under circumstances where no order of superposition has been made out. For instance, the general sequence of mammalian types having now been settled by the law of superposition, the horizon of a mammaliferous deposit may be approximately determined by the grade or degree of evolution denoted by its mammalian fossils.

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[1] Consult the papers of Prof. Marsh quoted on p. 653, and see especially the plate in the second paper in which the successive mammalian zones in the Geological Record of North America are given.

Thus, should remains be generically abundant, differing from those now living and presenting none of the extreme contrasts which are now found among our higher animals, should they embrace neither true ruminants, nor solipedes, nor proboscidians, nor apes, they might with high probability be referred to the Eocene period.[1] Reasoning of this kind must be based, however, upon a wide basis of evidence, seeing that the progress of development has been far from equal in all ranks of the animal world.

Observations made over a large part of the surface of the globe have enabled geologists to divide the stratified part of the earth's crust into systems, formations, and groups (p. 678). These subdivisions are frequently marked off from each other by lithological characters. But, as already remarked, mere lithological differences afford at the best but a limited and local ground of separation. Two masses of sandstone, for example, having exactly the same general external and internal characters, may belong to very different geological periods. On the other hand, a series of limestones in one locality may be the exact chronological equivalent of a set of sandstones and conglomerates at another, and of a series of shales and clays at a third.

Some clue is accordingly needed, which will permit the divisions of the stratified rocks to be grouped and compared chronologically. This fortunately is well supplied by their characteristic fossils. Each formation being distinguished by its own assemblage of organic remains, it can be followed and recognised even amid the crumplings and dislocations of a disturbed region. The same general succession of organic types has been observed over a large part of the world, though, of course, with important modifications in different countries. The similarity of succession has been called *homotaxis*—a term which expresses the fact that the order in which the leading types of organised existence have appeared upon the earth has been similar even in widely separated regions.[2]

It is evident that, in this way, a method of comparison is furnished whereby the stratified groups of different parts of the earth's crust can be brought into relation with each other. We find, for example, that a certain group of strata is characterised in Britain by certain genera and species of corals, brachiopods, lamellibranchs, gasteropods, and cephalopods. A group of rocks in Bohemia, differing more or less from the British type in lithological aspect, contains on the whole the same genera, and some even of the same species. In Scandinavia, a set of beds may be seen, unlike perhaps in external characters to the British type, but yielding many of the same fossils. In Canada and parts of the northern United States, other rocks enclose some of the same, and of closely allied genera and species. All these groups of strata, having the same general facies of organic remains, are classed together as *homotaxial*, that is, as having been deposited during the same relative period in the general progress of life in each region.

It was at one time believed, and the belief is still far from extinct, that groups of strata, characterised by this community or resemblance of organic remains, were chronologically contemporaneous. But such an inference rests upon most insecure grounds. We may not be able to disprove the assertion that the strata were strictly coeval, but we have only to reflect on the present conditions of zoological and botanical distribution, and of modern sedimentation, to be assured that the assertion of contemporaneity is a mere assumption. Consider, for a moment, what would happen were the present surface of any portion of central or southern Europe to be submerged beneath the sea, covered with marine deposits, and then re-elevated into land. The river-terraces and lacustrine marls formed before the time of Julius Cæsar could not be distinguished by any fossil tests from those laid down in the days of Victoria, unless, indeed, traces of human implements were obtainable whereby the progress of civilisation during 2000 years might be indicated. So far as regards the shells, bones, and plants preserved in the various formations, it would be absolutely impossible to discriminate their relative dates; they would be classed as "geologically contemporaneous," that is, as having been formed during the same period in the history of life in the European area; yet there might be a difference of 2000 years or more between many of them. Strict contemporaneity cannot be asserted of any strata merely on the ground of similarity or identity in fossils.

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[1] Gaudry, 'Les Enchainements du Monde Animal,' 1878, p. 246.

[2] Huxley, *Q. J. Geol. Soc.* xviii. (1862) p. xlvi.

But the phrase "geologically contemporaneous" is too vague to have any chronological value except in a relative sense. To speak of two formations as "contemporaneous," which may have been separated by thousands of years, seems rather a misuse of language, though the phraseology has now gained such a footing in geological literature as probably to be inexpugnable. If we turn again for suggestions to the existing distribution of life on the earth (though it is probable that formerly, and particularly among the earlier geological periods, there was considerably greater uniformity in zoological distribution than there is now), we learn that similarity or identity of species and genera holds good, on the whole, only for limited areas, and consequently, if applied to wide geographical regions, ought to be an argument for diversity rather than for similarity of age. If we suppose the British seas to be raised into dry land, so that the organic relics, preserved in their sands and silts, could be exhumed and examined, a general type or common facies would be found, though some species would be more abundant in or entirely confined to the north, while others would show a greater development in the opposite quarter. Still, there would be such a similarity throughout the whole, that no naturalist would hesitate to regard the organisms as those of one biological province, and belonging to the same great geological period. The region is so small, and its conditions of life so uniform and uninterrupted, that no marked distinction can be drawn between the forms of life in its different parts.

Widening the area of observation, we perceive that as we recede from any given point on the earth's surface the existing forms of life gradually change. Vegetation alters its aspect from climate to climate, and with it come corresponding transformations in the characters of insects, birds, and wild animals. A lake-bottom would preserve one suite of organisms in England, but a very different group at the foot of the Himalaya Mountains, yet the deposits at the two places might be absolutely coeval, even as to months and days. If, therefore, in the geological past there has been, as there is now, a grading of plants and animals in great biological provinces, marked off by differences of contour, climate, and geological history, we must conclude that, while strict contemporaneity cannot be predicted of deposits containing the same organic remains, it may actually be true of deposits in which they are quite distinct.[1]

If, then, at the present time, community of organic forms, except in the case of some almost world-wide species, obtains only in restricted districts, regions, or provinces, it may have been more or less limited also in past time. Similarity or identity of fossils among formations geographically far apart, instead of proving contemporaneity, may be compatible with great discrepancies in the relative epochs of deposit. For, on any theory of the origin of species, the spread of a species, still more of any group of species, to a vast distance from the original centre of dispersion, must in most cases have been inconceivably slow. It doubtless occupied so prolonged a time as to allow of almost indefinite changes in physical geography. A species may have disappeared from its primeval birthplace, while it continued to flourish in one or more directions along its outward circle of advance. The date of the first appearance and final extinction of that species would thus differ widely, according to the locality at which we might examine its remains.

The grand march of life, in its progress from lower to higher forms, has unquestionably been broadly alike in all quarters of the globe. But nothing seems more certain than that its rate of advance has not everywhere been the same. It has moved unequally over the same region. A certain stage of progress may have been reached in one quarter of the globe many thousands of years before it was reached in another; though the same general succession of organic types might be found in each region. At the present day, for example, the higher fauna of Australia is more nearly akin to that which flourished in Europe far back in Mesozoic time than to the living fauna of any other region of the globe. There seems also to be now sufficient evidence to warrant the assertion that the progress of terrestrial vegetation has at some geological periods and in some regions, been in advance of that of the marine fauna (see p. 668). Hence arise glaring anomalies in the attempts to group the geological formations of distant countries in conformity with European standards. As Mr. Blanford has well remarked, "in instances of conflicting evidence between terrestrial or freshwater faunas and floras on the one side, and marine faunas on the other, the geological age indicated by the latter is probably correct, because the contradictions which prevail between the evidence afforded by successive terrestrial and freshwater beds are unknown in marine deposits; because the succession of terrestrial animals and plants in time has been different from the succession of marine life; and because in all past times the differences between the faunas of distant lands have probably been, as they now are, vastly greater than the differences between the animals and plants inhabiting the different seas and oceans."[1]

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[1] The present geographical distribution of plants and animals has a profound geological interest, but cannot be properly discussed in this volume. The student will find it luminously treated in Darwin's 'Origin of Species,' chaps. xii. and xiii.; Lyell's 'Principles of Geology,' chaps. xxxviii.-xli.; and in Wallace's 'Geographical Distribution of Animals,' 2 vols. 1876, and his 'Island Life,' 1880.

Notwithstanding such exceptions, it may be asserted that in every country where the fossiliferous geological formations are well displayed and have been properly examined, a similar general order of organic succession can be made out among them. Their relative age within a limited geographical area can be demonstrated by the law of superposition. When, however, the rocks of distant countries are compared, all that we can safely affirm regarding them is that those containing the same or a representative assemblage of marine organic remains belong to the same epoch in the history of biological progress in each area. They are *homotaxial*; but we cannot assert that they are contemporaneous unless we are prepared to include within that term a vague period of many thousands of years.

3. Imperfection of the Geological Record.[2]—Since the statement was made by Darwin, geologists have more fully recognised that the history of life has been very imperfectly preserved in the stratified parts of the earth's crust. Apart from the fact that, even under the most favourable conditions, only a small proportion of the total flora and fauna of any period would be preserved in the fossil state, enormous gaps occur where, from non-deposit of strata, no record has been preserved at all. It is as if whole chapters and books were missing from a historical work. But even where the record may originally have been tolerably full, powerful dislocations have often thrown considerable portions of it out of sight. Sometimes extensive metamorphism has so affected the rocks that their original characters, including their organic contents, have been destroyed. Oftenest of all, denudation has come into play, and vast masses of strata have been entirely worn away, as is shown not only by the erosion of existing land-surfaces, but by the abundant unconformabilities in the structure of the earth's crust.

While the mere fact that one series of rocks lies unconformably on the denuded surface of another, proves the lapse of an interval between them, the relative length of this interval may sometimes be demonstrated by means of fossil evidence, and by this alone. Let us suppose, for example, that a certain group of formations has been disturbed, upraised, denuded, and covered unconformably by a second group. In lithological characters, the two may closely resemble each other, and there may be nothing to show that the gap represented by their unconformability is of an important character. In many cases, indeed, it would be quite impossible to pronounce any well-grounded judgment as to the length of interval, even measured by the vague relative standards of geological chronology. But if each group contains a well-preserved suite of organic remains, it may not only be possible, but easy, to say how much of the known geological record has been left out between the two sets of formations. By comparing the fossils with those obtained from regions where the geological record is more complete, it may be ascertained, perhaps, that the lower rocks belong to a certain platform or stage in geological history which, for our present purpose, we may call D, and that the upper rocks can, in like manner, be paralleled with stage H. It would be then apparent that, at this locality, the chronicles of three great geological periods, E, F, and G, were wanting, which are elsewhere found to be intercalated between D and H. The lapse of time represented by this unconformability would thus be equivalent to that required for the accumulation of the three missing series in those regions where, sedimentation having been more continuous, the record of them has been preserved.

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[1] Mr. Blanford, in his suggestive address to the Geological Section of the British Association at the Montreal meeting, from which the above quotation is taken, gives some examples of the contradictions involved in attempts to correlate distant deposits by means of land and freshwater faunas and floras. The Damuda beds of India, as he points out, contain a flora with middle Jurassic affinities, but the fauna of the overlying Panchet beds is rather Triassic or even Permian. Still more striking is the example furnished by the Lower Coal measures of New South Wales, where plants which botanists unhesitatingly pronounced to be of Jurassic types are found in the same stratified deposits with undoubted Carboniferous Limestone marine organisms (*Orthoceras*, *Conularia*. *Spirifer*, *Fenestella*, &c.) Mr. Blanford has returned to this subject in his presidential addresses to the Geological Society. *Quart. Journ.* xlv. (1889) p. 72, xlvi. (1890) p. 104.

[2] See p. 674

But fossil evidence may be made to prove the existence of gaps which are not otherwise apparent. As has been already remarked, changes in organic forms must, on the whole, have been extremely slow in the geological past. The whole species of a sea-floor could not pass entirely away, and be replaced by other forms, without the lapse of long periods of time. If, then, among the conformable stratified deposits of former ages, we encounter abrupt and important changes in the facies of the fossils, we may be certain that these must mark omissions in the record, which we may hope to fill in from a more perfect series elsewhere. The striking palæontological contrasts between unconformable strata are sufficiently explicable. It is not so easy to give a satisfactory account of those which occur where the strata are strictly conformable, and where no evidence can be observed of any considerable change of physical conditions at the time of deposit. A group of quite conformable strata, having the same general lithological characters throughout, may be marked by a great discrepance between the fossils of the upper and the lower part. A few species may pass from the one into the other, or perhaps every species may be different. In cases of this kind, when proved to be not merely local but persistent over considerable areas, we must admit, notwithstanding the apparently undisturbed and continuous character of the original deposition of the strata, that the abrupt transition from the one facies of fossils to the other represents a long interval of time which has not been recorded by the deposit of strata. Sir A. C. Ramsay, who called attention to these gaps, termed them "breaks in the succession of organic remains."[1] They occur abundantly among the European Palæozoic and Secondary rocks, which, by means of them, can be separated into zones and sections. But though traceable over wide regions, they were probably not general over the whole globe. There have never been any universal interruptions in the continuity of the chain of being, so far as geological evidence can show. The breaks or apparent interruptions no doubt exist only in the sedimentary record, and may have been produced by geological agencies of various kinds, such as cessation of deposit from failure of sediment owing to seasonal or other changes; alteration in the nature of the sediment or character of the water; variations of climate from whatever cause; elevation or subsidence by subterranean movements, bringing successive submarine zones into less favourable conditions of temperature, &c.; and volcanic discharges. The physical revolutions, which brought about the breaks, were no doubt sometimes general over a whole zoological province, more frequently over a minor region. Thus, at the close of the Triassic period the inland basins of central, southern, and western Europe were effaced, and another and different geographical phase was introduced which permitted the spread of the peculiar fauna of the "Avicula contorta zone" from the south of Sweden to the plains of Lombardy, and from the north of Ireland to the eastern end of the Alps. This phase in turn disappeared to make way for the Lias with its numerous "zones," each distinguished by the maximum development of one or more species of ammonite.[1] These successive geographical revolutions must, in many cases, have caused the complete extinction of genera and species possessing a small geographical range. Nevertheless, it must be admitted that in many intances where fossil species have a wide geographical extension, but a very limited stratigraphical range, such as the Silurian graptolites and Jurassic ammonites, no satisfactory evidence has been adduced to connect the change of species with geographical revolutions. There may be some biological law governing such organic mutations, which is not yet perceived.

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[1] *Q. J. Geol. Soc.* xix. xx. Presidential Addresses.

It is abundantly clear, however, that the geological record, as it now exists, is at the best but an imperfect chronicle of geological history. In no country is it complete. The lacunæ of one region may be supplied from another; yet in proportion to the geographical distance between the localities where the gaps occur and those whence the missing intervals are supplied, the element of uncertainty in our reading of the record is increased. The most desirable method of research is to exhaust the evidence for each area or province, and to compare the general order of its succession as a whole, with that which can be established for other provinces. It is, therefore, only after long and patient observation and comparison that the geological history of different quarters of the globe can be correlated.[2]

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[1] Consult on this subject the memoirs on Jurassic Geography of the late Prof. Neumayr, quoted *ante*, p. 655.

[2] For an example of the working out from fossil evidence of the history of the various provinces or regions of a large area of the earth's surface during an ancient geological period see the digest given by Professor Hyatt of what is known of the Jurassic tracts of Europe, in his essay on the 'Genesis of the Arietidæ,' chapter iv.

4. **Subdivisions of the Geological Record by means of fossils.**—As fossil evidence furnishes a much more satisfactory and widely applicable means of subdividing the stratified rocks of the earth's crust than mere lithological characters, it is made the basis of the geological classification of these rocks. Thus, a particular stratum may be ascertained to be marked by the occurrence in it of various fossils, one or more of which may be distinctive, either from occurring in no other bed above and below, or from special abundance in that stratum. These species may, therefore, be used as a guide to the occurrence of the bed in question, which may be called by the name of the most abundant species. In this way, a geological horizon or zone is marked off, and geologists thereafter recognise its position in the geological series. But before such a generalisation can be safely made, we must be sure that the species in question really never does characterise any other platform. This evidently demands wide experience over an extended field of observation. The assertion that a particular species or genus occurs only on one horizon, or within certain limits, manifestly rests on negative evidence as much as on positive. The palæontologist who makes it cannot mean more than that he knows the species or genus to lie on that horizon, or within those limits, and that, so far as his own experience and that of others goes, it has never been met with beyond the limits assigned to it. But a single instance of the occurrence of the fossil in a different zone would greatly damage the value of his generalisation, and a few such cases would demolish it altogether. The genus *Arethusina*, for example, had long been known as a characteristic trilobite of the lower zones of the third or highest fauna of the Bohemian Silurian basin. So abundant is one species (*A. Koninckii*) that Barrande collected more than 6000 specimens of it, generally in good preservation. But no trace of it had ever been met with towards the upper limit of the Silurian fauna. Eventually, however, a single specimen of a species so nearly identical as to be readily pronounced the same was disinterred from the upper Devonian rocks of Westphalia—a horizon separated from the upper limit of the genus in Bohemia by at least half of the vertical height of the Upper Silurian and by the whole of the Lower and Middle Devonian rock-groups.[1] Such an example teaches the danger of founding too much on negative data. To establish a geological horizon on limited fossil evidence, and then to assume the identity of all strata containing the same fossils, is to reason in a circle, and to introduce utter confusion into our interpretation of the geological record. The first and fundamental point is to determine accurately the superposition of the strata. Until this is done, detailed palæontological classification may prove to be worthless.

From what has been above advanced, it must be evident that, even if the several groups in a series or system of rocks in any district or country have been found susceptible of minute subdivision by means of their characteristic fossils, and if, after the lapse of many years, no discovery has occurred to alter the established order of succession of these fossils, nevertheless the subdivisions may only hold good for the région in which they have been made. They must not be assumed to be strictly applicable everywhere. Advancing into another district or country, where the petrographical characters of the same formation or system indicate that the original conditions of deposit must have been very different, we ought to be prepared to find a greater or less departure from the first observed, or what we unconsciously and not unnaturally come to look upon as the normal, order of organic succession. There can be no doubt that the appearance of new organic forms in any locality has been in large measure connected with such physical changes as are indicated by diversities of sedimentary materials and arrangements. The Upper Silurian stages, for example, as studied by Murchison in Shropshire and the adjacent counties, present a clear sequence of strata well defined by characteristic fossils. But within a distance of sixty miles, it becomes impossible to establish these subdivisions by fossil evidence. Again, in Bohemia and in Russia we meet with still greater departures from the order of appearance in the original Silurian area, some of the most characteristic Upper Silurian organisms being there found beneath strata replete with records of Lower Silurian life. Nevertheless, the general succession of life from Lower to Upper Silurian types remains distinctly traceable. Still more startling are the anomalies, already referred to, where the succession of terrestrial organisms in distant regions is compared with that of the associated marine forms; as where, in Australia, a flora with Jurassic affinities and a Carboniferous Limestone fauna were contemporaneous. Such facts warn us against the danger of being led astray by an artificial precision of palæontological detail. Even where the palæontological sequence is best established, it rests, probably in most cases, not merely upon the actual chronological succession of organic forms, but also, far more than is usually imagined, upon original accidental differences of local physical conditions. As these conditions have constantly varied from region to region, it must comparatively seldom happen that the same minute palæontological subdivisions, so important and instructive in themselves, can be identified and paralleled, except over comparatively limited geographical areas. The remarkable "zones" of the Lias, for instance, which have been recognised over central and western Europe, cease to be traceable as we recede from their original geographical province.

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[1] Barrande, 'Réapparition du genre Arethusina,' Prague, 1868.

§ v. **Bearing of Palæontological data upon Evolution.** — Since the researches of William Smith at the end of last century, it has been well understood that the stratified portion of the earth's crust contains a suite of organic remains in which a gradual progression can be traced, from simple forms of invertebrate life among the older rocks to the most highly differentiated mammalia of the present time. Until the appearance of Darwin's 'Origin of Species' in 1859, the significance of this progression, and its connection with the biological relations of existing faunas and floras were only dimly perceived, though Lamarck had proposed a theory of development, in support of which appeals had been made to the organic succession revealed by the geological record. Darwin, arguing that, instead of being fixed or but slightly alterable forms, species might be derived from others, showed that processes were at work, whereby it was conceivable that the whole of the existing animal and vegetable worlds might have descended from, at most, a very few original forms. From a large array of facts, drawn from observations made upon domestic plants and animals, he inferred that, from time to time, slight peculiarities due to differences of climate, &c., appear in the offspring which were not present in the parent, that these peculiarities may be transmitted to succeeding generations, especially where from their nature they are useful in enabling their possessors to maintain themselves in the general struggle for life. Hence varieties, at first arising from accidental circumstances, may become permanent, while the original form from which they sprang, being less well adapted to hold its own, perishes. Varieties become species, and specific differences pass in a similar way into generic. The most successful forms are, by a process of "natural selection," made to overcome and survive those that are less fortunate, the "survival of the fittest" being the general law of nature. The present varied life of the globe may thus, according to Darwin, be explained by the continued accumulation, perpetuation, and increase of differences in the evolution of plants and animals during the whole of geological time. Hence the geological record should contain a more or less full chronicle of the progress of this long history of development.

It is now well known that in the embryonic development of animals, there are traces of a progress from lower or more generalised to higher or more specialised types. Since Darwin's great work appeared, naturalists have devoted a vast amount of research to this subject, and have sought with persevering enthusiasm for any indications of a relation between the order of appearance of organic forms in time and in embryonic development, and for evidence that species and genera of plants and animals have come into existence in the order which, according to the theory of evolution, might have been anticipated.

It must be conceded that, on the whole, the testimony of the rocks is in favour of the doctrine of evolution. That there are difficulties still unexplained, must be frankly granted. Darwin strongly insisted, and with obvious justice, on the imperfection of the geological record, as one great source of these difficulties. Objections to the development theory may, as shown by Mr. Carruthers, be drawn from the observed order of succession of plants, and the absence of transitional forms among them. Ferns, equisetums, and lycopods appear as far back as the Old Red Sandstone, not in simple or more generalised, but in more complex structures than their living representatives. The earliest known conifers were well-developed trees, with woody structure and fruits as highly differentiated as those of the living types. The oldest dicotyledons yet found, those of the Cretaceous formations, contain representatives of the three great divisions of *Apetalæ*, *Monopetalæ*, and *Polypetalæ*, in the same deposit. These "are not generalised types, but differentiated forms which, during the intervening epochs, have not developed even into higher generic groups."[1]

Professor A. Agassiz has drawn attention to the parallelism between embryonic development and palæontological history. Taking the sea-urchins as an illustrative group, he points out the interesting analogies between the immature conditions of living forms and the appearance of corresponding phases in fossil genera. He admits, however, that no early type has yet been discovered whence star-fishes, sea-urchins, or ophiurans might have sprung; that the several orders of echinoderms appear at the same time in the geological record, and that it is impossible to trace anything like a sequence of genera or direct filiation in the palæontological succession of the echinids, though he does not at all dispute the validity of the theory which regards the present echinids as having come down in direct succession from those of older geological times.[1] In the case of the numerous genera which have continued to exist without interruption from early geological periods, and have been termed "persistent types," it is impossible not to admit that the existing forms are the direct descendants of those of former ages. If, then, some genera have unquestionably been continuous, the evolutionist argues, it may reasonably be inferred that continuity has been the law, and that even where the successive steps of the change cannot be traced, every genus of the living world is genetically related to other genera now extinct.

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[1] Carruthers. *Geol. Mag.* 1876, p. 362.

Professor A. Hyatt, who has closely studied the Cephalopoda, regards them as furnishing clear evidence of evolution. Returning to some of the ideas of Lamarck on development, he concludes that "the efforts of the orthoceratite to adapt itself fully to the requirements of a mixed habitat, gave the world the Nautiloidea; the efforts of the same type to become completely a littoral crawler, developed the Ammonoidea." He thinks that, on the whole, the observed succession of the organisms in time coincides with what on the theory of evolution it ought to have been. "The straight cones predominate in Silurian and earlier periods, while the loosely coiled are much less numerous, and the close-coiled and involute, though present, are extremely rare." He believes that traces of this succession may be found in the structure of the shells themselves. The nautilus, in its embryological development and subsequent growth, passes through the stages of the nearly or quite straight shell, then of a slightly curved shell, and then of a completely curved shell, the spiral being continued till sometimes the inner whorls are entirely enveloped in the outer.[2]

Neumayr, from a prolonged study of European Jurassic and Cretaceous cephalopods, concluded that "propagation, filiation, and migration are sufficient to explain the origin of the whole Jurassic Ammonite and Belemnite fauna of central Europe. There is nothing to warrant the supposition of any new creation, but all the known facts are in harmony with the theory of descent."[3]

Among the fossil mammalia many indications have been pointed out of an evolution of structure. Of these, one of the best known and most striking is the genealogy of the horse, as worked out by Professor O. C. Marsh.[4] The original, and as yet undiscovered, ancestor of our modern horse had five toes on each foot. In the oldest known equine type (Eohippus—an animal about the size of a fox, belonging to the early part of the Eocene period) there were four well-developed toes, with the rudiment of a fifth, on each fore-foot, and three on each hind-foot. In a later part of the same geological period appeared the Orohippus, a creature of about the same size, but with only four toes in front and three behind. Traced upwards into younger divisions of the Tertiary series, the size of the animal increases, but the number of digits diminishes, until we reach the modern Equus, with its single toe and rudimentary splint-bones.

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[1] *Ann. Mag. Nat. Hist.* Nov. 1880, p. 369. "Report on Echinoidea," *Challenger* Expedition, vol. iii. p. 19.

[2] *Science*, iii. (1884) pp. 122, 145. For an elaborate presentation of his views see his essay on the 'Genesis of the Arietidæ,' *Mem. Mus. Comparat. Zool. Harvard*, xvi. (1889), where also full references to the literature of the subject treated of by him will be found.

[3] *Jahrb. Geol. Reichsanst.* xxviii. (1878) p. 78; also *Abhandl. Geol. Reichsanst.* 1873; *Sitzb. K. Akad. Wiss. Wien*, lxxi. (1875) p. 639. *Verh. Geol. Reichsanst.* 1880, p. 83 (in reply to the anti-Darwinian views of T. Fuchs, *op. cit.* 1879, 1880), and his memoirs already cited on p. 655. W. Branco, *Z. Deutsch. Geol. Ges.* xxxii. (1880) p. 596. An example of the tracing of pedigree among trilobites was supplied by R. Hoernes, *Jahrb. Geol. Reichsanst.* xxx. (1880) p. 651. On the geological history and affiliations of the Palæozoic invertebrates, the student should consult Prof. Gaudry's 'Les Enchaînements du Monde Animal: Fossiles Primaires,' 1883.

[4] *Amer. Journ. Sci.* 1879, p. 499. Consult also his interesting paper on "Recent polydactyle Horses," *op. cit.* xlii. (1892) p. 339.

Another remarkable example, that of the camels, is cited by Professor E. D. Cope. The succession of genera is seen in the same parts of the skeleton as in the case of the horse. The metatarsal and metacarpal bones are or are not co-ossified into a cannon bone ; the first and second superior incisor teeth are present, rudimentary or wanting, and the premolar number from four to one. The chronological succession of genera is given by Mr. Cope as follows :

	No cannon bone.	Cannon bone present.		
	Incisor teeth present.	Incisors 1 and 2 wanting.		
	4 premolars.	3 premolars.	2 premolars.	1 premolar.
Lower Miocene .	Poebrotherium.			
Upper Miocene . .	Protolabis. Procamelus.	Pliauchenia.		
Pliocene and recent.			Camelus.	Auchenia.

According to this table, the Camelidæ have gradually undergone a consolidation of the bones of the feet, with a great reduction in the number of the incisor or premolar teeth. Mr. Cope indicates an interesting parallel between the palæontological succession and the embryonic history of the same parts of the skeleton in the living camel.[1] Among the Carnivora, as M. Gaudry has pointed out, it is possible not only to trace the ancestry of existing species, but to discover traits of union between genera which at present seem far removed.[2]

It is not necessary here to enter more fully into the biological aspect of this wide subject. While the doctrine of evolution has now obtained the assent of the great majority of naturalists all over the globe, even the most strenuous upholder of the doctrine must admit that it is attended with palæontological difficulties which no skill or research has yet been able to remove. The problem of derivation remains insoluble, nor perhaps may we hope for any solution beyond one within the most indefinite limits of correctness.[3] But to the palæontologist, it is a matter of the utmost importance to feel assured that, though he may never be able to trace the missing links in the chain of being, the chain has been unbroken and persistent from the beginning of geological time.

It was remarked above (p. 660) that, while the general march of life has been broadly alike all over the world, progress has been more rapid in some regions, and likewise in some grades of organic being, than in others. The evolution of terrestrial plants and animals appears to have been much less uniform than that of marine life, at least than that of the marine mollusca. It has been suggested that the climatic changes, which have had so dominant an influence in evolution, would affect land-plants before they influenced marine animals. Certainly a number of instances is known where an older type of marine fauna is associated with a younger type of terrestrial flora. Besides those already cited (p. 661), reference may be made to the flora of Fünfkirchen in Hungary, which, though Triassic in type, occurs in strata which have been classed with the Palæozoic Zechstein; and to the Upper Cretaceous flora of Aix la Chapelle, which, with its numerous dicotyledons, has a much more modern aspect than the contemporaneous fauna. In the Western Territories of North America, much controversy has been raised as to the position of the "Laramie series," its rich terrestrial flora having an undoubted Tertiary facies, while its fauna is Cretaceous. According to Fuchs, the most important turning-point in the history of the plant-world is to be found not, as in the case of the terrestrial fauna, between the Sarmatian stage and the *Congeria*-beds, but on an older horizon, namely between the first and second Mediterranean stage.[1] Nor is this intercalation of types characteristic of other periods entirely confined to the vegetable world. Examples may be found of survivals of types of terrestrial animals when the contemporaneous marine fauna has become distinctly more modern. The present mammals of Australia and New Guinea are more allied to forms that lived in Mesozoic time than to those now living in other countries. The remarkable Miocene mammalian fauna of Pikermi has been found to lie upon strata containing Pliocene marine shells.

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[1] *American Naturalist*, 1880, p. 172. M. Gaudry traces an analogous process in the foot-bones of the ruminants of Tertiary time, 'Les Enchaînements du Monde Animal,' vol. i. p. 121.

[2] *Op. cit.* p. 210.

[3] A. Agassiz, *Ann. Mag. Nat. Hist.* 1880, p. 372.

From what has now been stated, it will be understood that the existence of any living species or genus of plant or animal, within a certain geographical area, is a fact which cannot be explained except by reference to the geological history of that species or genus. The existing forms of life are the outcome of the evolution which has been in progress during the whole of geological time. From this point of view, the investigations of palæontological geology are invested with the profoundest interest, for they bring before us the history of that living creation of which we form a part.

§ vi. The collecting of Fossils.—Some practical suggestions regarding the search for fossils may be of service to the student. Any sedimentary rock may possibly enclose the remains of plants or animals. All such rocks should therefore be searched for fossils. A little practice will teach the learner that some kinds of sedimentary rocks are much more likely than others to yield organic remains. Limestones, calcareous shales, and clays are often fossiliferous; coarse sandstones and conglomerates are seldom so. Yet it will not infrequently be found that rocks which might be expected to contain fossils are barren, while even coarse conglomerates may, in rare cases, yield the teeth and bones of vertebrates or other durable relics of once living things. The peculiarities of the rocks of each district must, in this respect, be discovered by actual careful scrutiny.

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[1] E. Weiss, *Neues Jahrb.* 1878, p. 180; also *Z. Deutsch. Geol. Ges.* xxix. p. 252.

As organic remains usually differ more or less, both in chemical composition and in minute texture, from the matrix in which they are imbedded, they weather differently from the surrounding rock. In some instances, where they are more durable, they project in relief from a weathered surface; in others they decay, and leave, as cavities, the moulds in which they have lain. One of the first requisites, therefore, in the examination of any rock for fossils is a careful search of its weathered parts. In the great majority of cases, its fossiliferous or non-fossiliferous character may thereby be ascertained.

When indications of fossils have been obtained, the particular lithological characters of the part of the rock in which they occur should be noted. It will often be found that the fossils are either confined to, or are more abundant and better preserved in, certain zones. These zones should be explored before the rest of the rock is examined in detail. Where fossils decay on exposure, the rock containing them must be broken open so as to reach its fresher portions. Where the rock is not disintegrated in weathering, it must likewise be split up in the usual way. But where it crumbles under the influence of the weather, and allows its fossils to become detached from their matrix, its débris should be examined. Shales and clays are particularly liable to this kind of disintegration, and are consequently deserving of the fossil-collector's closest attention, since from their decaying surfaces he may often gather the organisms of past times, as easily as he can pick up shells on the present sea-shore.

But the task of the collector does not end when he has broken open several tons, perhaps, of fresh rock, and has searched among the weathered débris until he can no longer meet with any forms he has not already found. In recent years, methods have been devised for enabling him to extract the minuter organisms from rocks. Some of these methods are described in the following pages.[1] They show that a deposit, otherwise supposed to be unfossiliferous, may be rich in foraminifera, entomostraca, &c., so that, besides the abundant fossils readily detected by the naked eye in a rock, there may be added a not less abundant and varied collection of microzoa.

As each variety of rock has its own peculiarities of structure, which may vary from district to district, the appliances of the fossil collector must likewise be varied to suit local requirements. The following list comprises his most generally useful accoutrements; but his own judgment will enable him to modify or supplement them according to his needs:—

List of Appliances useful in Fossil-collecting.

1. Several hammers, varying in size according to the nature of the rocks to be examined. Where these are tough and hard, a hammer weighing 2 lbs. may be needed. A small trimming hammer (6 oz.) for reducing the size of specimens is essential.
2. Several chisels of different sizes and shapes.
3. A small pick weighing 1 lb., useful for loosening blocks of rocks from their bed.
4. A small trowel, used for scooping up weathered débris of shale, &c.
5. A gardener's spade with circular cutting edge; of use in lifting slabs of shale.
6. Pair of strong pincers, like those used for cutting wire, for reducing specimens which might go to pieces under a blow of a hammer.
7. A collecting-bag (canvas or leather).

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[1] The following descriptions of methods of searching for fossil microzoa have been drawn up from notes for which I am indebted to Mr. James Bennie, Fossil Collector of the Geological Survey of Scotland, who has been singularly successful in increasing our knowledge of the minuter forms of animal life in the Carboniferous system.

8. A supply of nests of pill-boxes for more delicate specimens.
9. Brown and softer grey wrapping paper (old newspapers are serviceable).
10. Gummed labels, numbered to correspond with those in the collecting-book.
11. Note-book or collecting-book, in which, where practicable, each specimen is entered under its number, with all particulars of its exact locality, geological horizon, &c.
12. Fish-glue, a thin solution of which is useful to preserve specimens that may be liable to crack into pieces.

Weathered Shales.—The heaps of shale thrown out in quarrying operations, afford excellent ground for fossil-hunting. It is best to begin at the bottom of a heap, and to creep slowly along the same level for a dozen yards or so, where the ground to be examined is extensive; then to return along a band slightly higher, and so on backward and forward until the top is reached, which may be searched in breadths of a yard at a time. In this way, the more prominent fossils may be obtained. Large and thin fossils, such as shells of *Pecten*, *Modiola*, &c., which break into fragments in weathering must be sought for in the less decayed parts of the shale. When found, the matrix around them should be reduced to the desired size by means of pincers. They should then be wrapped up in a box, or, at least, secured against injury in the homeward transport, and as soon as possible thereafter should be dipped in a thin solution of fish-glue and allowed to dry slowly in the air. As a rule, particularly where the structure of a fossil is well preserved, it is desirable to retain also the surface of rock containing its impression, which not infrequently affords evidence of structure that may be less distinctly preserved on the counterpart, or side to which the main portion of the fossil has adhered.

Some fossils of great delicacy, such as fronds of *Fenestella*, which go to pieces as the rock weathers, may be extracted by an ingenious process devised by Mr. John Young, Curator of the Hunterian Museum, Glasgow University. If the shale on which such organisms lie is liable to go to pieces, it may be sufficiently secured for transport by being coated with a thin solution of gum, which is allowed to dry before the specimen is packed up. If the actually exposed face of the *Fenestella* is intended to be exhibited, it may be cleaned from the gum or from any adherent shale by being rubbed quickly with a wet nail-brush and wiped with a clean damp sponge, care being taken that the gum holding down the lower surface of the fossil is not softened, and that the shale does not get too wet. If, on the other hand, it is desirable to expose the face of the frond that adheres to the shale, this may be effected as follows. All trace of any gum that may have been used should be carefully removed. The specimen is then warmed before a fire, and a thin layer of asphalt is melted over it by means of a hot iron rod. If the frond to be lifted is large, a thick strong cake should be formed upon the specimen by using alternate layers of strong brown paper and asphalt, the paper always forming the outer surface of the cake. When the cohesion between the asphalt and the specimen is firm, the whole is then placed in water, when the shale generally crumbles down and can be removed, leaving the *Fenestella* adhering to the asphalt. In this way, the poriferous surface, which, for the most part, clings to the shale when the rock is broken open, is laid bare. By gently brushing the specimen with water, its minute structure may be revealed, the delicate network lying on the asphalt like a piece of lace upon a ground of black velvet. The cake of asphalt may then be shaped and mounted on a wooden tablet.[1]

But in most cases there are numerous minuter forms which escape notice, and which must be searched for in another way. To secure these, a little shale should be lifted with a trowel from the most weathered parts where fossils are visible, the trowel being gently pushed along so as to remove only the superficial layer, where the fossils are necessarily more abundant from the disintegration and removal of the shale by rain, sun and wind. If wet,' the shale thus collected should be thoroughly dried in an oven or before a fire. Thereafter, it is to be well soaked in water till it crumbles down; after gentle agitation, the muddy water should be poured off, the heavier particles being allowed to settle to the bottom. This process should be repeated till the sediment is so freed from clayey particles that it can be passed through sieves of different degrees of fineness. The several assortments thus obtained should then be boiled separately in a rather broad-bottomed goblet over a brisk fire for about half an hour, the boiling being continued with a change of water till little or no mud appears. The coarser parcels may then be dried and spread out on a school-slate, when, with lens and a camel-hair brush wetted at the point, the fossils may be easily picked out and dropped into a pill-box for further examination. The finer kinds may be separated into lighter and heavier portions by putting, say a handful of the thoroughly dried sediment into a bowl, and turning a gentle stream of water upon it, when the lighter grains float and may be decanted into another vessel. These floated parts include the smaller kinds of foraminifera and entomostraca, the plates, anchors, crosses, and other spicules of holothurians and sponges, fragments of polyzoa, shells, &c. The effect of boiling is to loosen these organisms from the matrix and to clean them more perfectly than can be done in any other way; the minuter forms float off as dust. By this method of detection and selection, fossils which occur only in the proportion of one in a thousand of the particles may be easily secured.

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[1] Mr. Young kindly revised for me this account of his asphalt-process.

Unweathered Shales.—*It often happens that along cliff-sections, on the banks* or beds of rivers or on the sea-shore, fossiliferous shales occur from which the weathered portions are continually washed or blown away, so that no opportunity occurs of adequately collecting the fossils from the exposed débris of the rocks. In such cases the solid, unweathered shale must be taken and treated somewhat differently. All layers of shale will not be found to be equally rich in microzoa, and it is desirable to try those first which seem most likely to yield satisfactory results—such, for instance, as those which are otherwise most fossiliferous. Where shale occurs in association with limestone, the portions just beneath or above the limestone should first be searched. The parts selected should be dried as thoroughly as possible in an oven or before a fire, and should then be put into water, and left there until they fall to pieces. The débris thus obtained is to be put into a rather wide-meshed sieve, and the coarser materials left behind may be again dried and steeped, this process being repeated two or three times, or until the fragments undergo no further subdivision. When thus reduced as much as possible, the débris should be boiled as above described. Some shales are completely disintegrated at once by boiling; others only after prolonged boiling, while some, though subdivided into small fragments, will not "dissolve," that is, will not break up into such fine particles as to remain in mechanical suspension in the water. Such obdurate varieties must be examined in bulk. In the Carboniferous system, the shales that boil down completely are those in which their component argillaceous particles have been compacted merely by pressure, or with such slight cementation as could be destroyed by boiling. They are usually grey beds, such as so often accompany limestones. The black shales, on the other hand, containing a considerable proportion of bituminous cement, will not thoroughly break up even after prolonged boiling.

The drying and steeping here described may be regarded as processes of rapid artificial weathering. The effects of the heat of a fire upon shale resemble those of the sun's rays, and the soaking in water is a counterpart of the action of rain. It is surprising how easily hard, compact shale, which can with difficulty be broken or split with a hammer, may, by the method above specified, be reduced to dust or to fine granular débris, from which even delicate shells may easily be picked out entire. One may thus experimentally learn how important a part in the disintegration of rocks must be taken by the alternate desiccation and saturation of their surfaces by sunshine and shower.

Limestone and Ironstone.—Among fossiliferous limestones, remarkable differences are observable in the lithological condition of the enclosed fossils, and in the ease with which they can be recognised and extracted. It is only by diligent practice that these peculiarities can be so mastered as to enable the observer to make an exhaustive collection from the rocks which he explores. In some limestones, the organic remains are specially abundant in particular layers or pockets. Fragments of these parts of the rock may be taken home, and their fossils may be extracted by fixing the block on a piece of lead 1 inch thick and about 6 inches square, and cutting out the desired specimens with hammer and chisel. Entomostraca, and other small organisms in which the valves are united, may also be obtained in a perfect condition from this class of rocks, by pounding fragments of the fossiliferous material with a hammer within the circle of a small iron ring or "washer," one-eighth of an inch in thickness. As the rock is crushed by the blows of the hammer the organisms jump out of the matrix, but are retained within the bounds of the ring, which also answers as a gauge, preventing the material from being broken too small. The pounded rock is afterwards washed free from dust, dried and searched as above directed. Many limestones reveal their fossils best on weathered surfaces. In such cases, it not infrequently happens that the upper part of the rock immediately below the soil or subsoil yields a richer harvest of good specimens than could be obtained by breaking open the fresh stone. Some of the rotten débris from the surface and fissures of the limestone should be carried home, washed and boiled, as in the treatment of shale. The minuter organisms may thus be recovered. and as these, when found in limestone, often differ in kind from those preserved in shale, no opportunity should be lost of searching for them. Soft, pulverulent limestones, such as chalk, should be gently levigated, the chalky water being poured off and fresh water being added, until a granular residue of foraminifera, ostracods, shell fragments, &c., is obtained. Nodules of limestone or ironstone often enclose fossils, but it is not always easy to split them open in such a way as to lay bare their organic nucleus. This, however, may frequently be effected by putting the nodule into a fire, and dropping it, when quite hot. into cold water.

Clays.—These may be successfully treated for microzoa in the manner above described for shales. Though they often contain much interstitial moisture they are not readily levigated in water until after they have been thoroughly dried in an oven, before a fire, or in the sun. When so treated they are easily reduced to fine mud, which may be removed in suspension until a granular residue is left, which may be searched for fossils. But as many of the minuter organisms float when loosened from the matrix, the muddy water should be passed through a brass-wire sieve as fine as muslin. If the meshes become clogged, so that the water will not flow readily through them, a few smart taps on the side of the sieve will clear them. Should some portions of the clay refuse to pass into muddy suspension, even after repeated trials, they will probably be levigated by boiling, as for shale. Treated as here recommended, many glacial clays, which, to the eye, appear hopelessly unfossiliferous, may thus be made to yield an interesting group of *Foraminifera*, *Entomostraca*, &c.[1]

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[1] By the methods here recommended large additions have been made to our knowledge of the microzoa of the past. (See, for example, Mr. H. B. Brady's researches on the Carboniferous *Foramanifera*, and Prof. T. R. Jones's and Mr. Kirkby's monograph on Carboniferous *Entomostraca*.) The existence of *Holothuridæ* in the Carboniferous sea has been discovered entirely by these means.

BOOK VI.

STRATIGRAPHICAL GEOLOGY.

THIS branch of the science arranges the rocks of the earth's crust in the order of their appearance, and interprets the sequence of events of which they form the records. Its province is to cull from other departments of geology the facts which may be needed to show what has been the progress of the planet, and of each continent and country on its surface, from the earliest times of which the rocks have preserved any memorial. Thus, from Mineralogy and Petrography, it obtains information regarding the origin and subsequent mutations of minerals and rocks. From Dynamical Geology, it learns by what agencies the materials of the earth's crust have been formed, altered, broken or upheaved. From Geotectonic Geology, it understands in what manner these materials have been built up into the complicated crust of the earth. From Palæontological Geology, it receives, in well-determined fossil remains, a clue by which to follow the relative chronology of stratified formations, and to trace the grand onward march of organised existence upon the planet. Stratigraphical geology thus gathers up the sum of all that is ascertained by other departments of the science, and makes it subservient to the interpretation of the geological history of the earth.

The leading principles of stratigraphy may be summed up as follows :—

1. In every stratigraphical research, the fundamental requisite is to establish the true or original order of superposition of the strata. Until this is accomplished by careful study of the actual relations of the rocks in the field, it is impossible to arrange relative dates and make out the sequence of geological history.

2. The stratified portion of the earth's crust, or Geological Record, may be subdivided into natural groups or "formations" of strata, each marked throughout by some common *facies* of organic remains, that is by the occurrence of some characteristic genera or species or a general resemblance in their palæontological type or character,[1] or, for limited tracts of country, by some common lithological features.

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[1] The student may consult an interesting paper by Prof. E. Renevier (*Arch. Sci. Phys.*

3. Living species of plants and animals can be traced downward into the more recent geological formations; but grow fewer in number as they are followed into more ancient deposits. With their disappearance, we encounter other species and genera which are no longer living. These in turn may be traced backward into earlier formations, till they too cease, and their places are taken by yet older forms. It is thus shown that the stratified rocks contain the records of a gradual progression of organic types. A species which has once died out does not seem ever to have reappeared.

4. When the order of succession of organic remains among the stratified rocks of a district or country has once been accurately determined on the basis of the true stratigraphical order, it becomes an invaluable guide in the investigation of the relative age and structural arrangements of these rocks even in regions beyond that in which the organic succession has been first made out. Each zone or group of strata, being characterised by its own species or genera, may be recognised by their means, and the true succession of strata may thus be confidently established even in an area such as that of the Alps, wherein the rocks have been greatly fractured, folded, inverted, or metamorphosed.

5. The relative chronological value of the divisions of the Geological Record is not to be measured by mere depth of strata. While a great thickness of stratified rock may be reasonably assumed to mark the passage of a long period of time, it cannot safely be affirmed that a much less thickness elsewhere represents a correspondingly diminished period. The truth of this statement may sometimes be made evident by an unconformability between two sets of rocks, as has already been explained. The total depth of both groups together may be, say, 1000 feet. Elsewhere we may find a single unbroken formation reaching a depth of 10,000 feet; but it would be utterly erroneous to conclude that the latter represents ten times the duration indicated by the two former. So far from this being the case, it might not be difficult to show that the minor thickness of rock really denoted by far the longer geological interval. If, for instance, it could be proved that the upper part of both the sections lay on one and the same geological platform, but that the lower unconformable series in the one locality belonged to a far lower and older system of rocks than the base of the thick conformable series in the other, then it would be clear that the gap marked by the unconformability really indicated a longer period than the massive succession of deposits.

6. Fossil evidence furnishes the chief means of comparing the relative chronological value of groups of rock. A break in the succession of organic remains marks an interval of time often unrepresented by strata at the place where the break is found.[1] The relative importance of these breaks, and therefore, probably, the comparative intervals of time which

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Nat. Geneva (1884), xii. p. 297) on "Geological Facies." The total mean depth of the fossiliferous formations of Europe has been set down at 75,000 feet, or upwards of 14 miles.

[1] See *ante*, p. 662, and the classic essays of the late Sir A. C. Ramsay there cited.

they denote, may be estimated by the difference of the facies of the fossils on each side. If, for example, in one case we find every species to be dissimilar above and below a certain horizon, while in another locality only half of the species on each side of a band are peculiar, we naturally infer, if the total number of species seems large enough to warrant the inference, that the interval marked by the former break was very much longer than that marked by the latter. But we may go further, and compare by means of fossil evidence the relation between breaks in the succession of organic remains and the depth of strata between them.

Three series of fossiliferous strata, A, C, and H, may occur conformably above each other. By a comparison of the fossil contents of all parts of A, it may be ascertained that, while some species are peculiar to its lower, others to its higher portions, yet the majority extend throughout the group. If now it is found that, of the total number of species in the upper portion of A, only one-third passes up into C, it may be inferred with some probability that the time represented by the break between A and C was really longer than that required for the accumulation of the whole of the group A. It might even be possible to discover elsewhere a thick intermediate group B filling up the gap between A and C. In like manner, were it to be discovered that, while the whole of the group C is characterised by a common suite of fossils, not one of the species and only one half of the genera pass up into H, the inference could hardly be resisted that the gap between the two groups marks the passage of a far longer interval than was needed for the deposition of the whole of C. And thus we reach the remarkable conclusion that, thick though the stratified formations of a country may be, in some cases they may not represent so long a total period of time as do the gaps in their succession,—in other words, that non-deposition has been in some areas more frequent and prolonged than deposition, or that the intervals of time which have been recorded by strata have sometimes not been so long as those which have not been so recorded.

In all speculations of this nature, however, it is necessary to reason from as wide a basis of observation as possible, seeing that so much of the evidence is negative. Especially needful is it to bear in mind that the cessation of one or more species, at a certain line among the rocks of a particular district, may mean nothing more than that, owing to some change in the conditions of life or of deposition, these species were compelled to migrate, or became locally extinct, at the time marked by that line. They may have continued to flourish abundantly in neighbouring districts for a long period afterward. Many examples of this obvious truth might be cited. Thus, in a great succession of mingled marine, brackish-water, and terrestrial strata, like that of the Carboniferous Limestone series of Scotland, corals, crinoids, and brachiopods abound in the limestones and accompanying shales, but grow fewer or disappear in the sandstones, ironstones, clays, and bituminous shales. An observer, meeting for the first time with an instance of this disappearance, and remembering what he had read about "breaks in succession," might be tempted to speculate about the extinction of these organisms, and their replacement by other and later forms of life, in the overlying strata. But further research would show him that, high above the plant-bearing sandstones and coals, lie other limestones and shales charged with the same marine fossils as before, and followed by still further groups of sandstones, coals, and carbonaceous beds and yet higher marine limestones. He would thus learn that the same organisms, after being locally exterminated, returned again and again to the same area when the conditions favourable for their migration reappeared and enabled them to reoccupy their former haunts. Such a lesson would probably teach him how largely the fauna entombed and preserved on any particular geological horizon has been influenced by the conditions of sedimentation, and that he should pause before too confidently asserting that the highest bed in which certain fossils can be detected, marks really their final appearance in the history of life. An interruption in the succession of fossils may be merely temporary or local, one set of organisms having been driven to a different part of the same region, while another set occupied their place until the first was enabled to return.

The remarkable limitation of certain species to a restricted vertical range in a continuous series of stratified deposits, as in the case of the Silurian graptolites and the Jurassic ammonites already cited, affords a valuable basis for stratigraphical arrangement and comparison. The succession of these species has been in some cases similar over such wide geographical areas that it is difficult to connect this organic sequence with any physical revolutions, of which indeed in a conformable series of sediments there may be little or no trace. As already suggested there may have been some biological law that governed these apparently rapid extinctions or replacements of organic forms, but which is not yet perceived or understood.

7. The Geological Record is at the best but an imperfect chronicle of the geological history of the earth. It abounds in gaps, some of which have been caused by the destruction of strata owing to metamorphism, denudation, or otherwise, some by original non-deposition, as above explained. Nevertheless it is from this record that the progress of the earth is chiefly traced. It contains the registers of the births and deaths of tribes of plants and animals, which have from time to time lived on the earth. Probably only a small proportion of the total number of species, which have appeared in past time, have been thus chronicled, yet, by collecting the broken fragments of the record, an outline at least of the history of life upon the earth can be deciphered.

It cannot be too frequently stated, nor too prominently kept in view, that, although gaps occur in the succession of organic remains as recorded in the rocks, there have been no such blank intervals in the progress of plant and animal life upon the globe. The march of life has been unbroken, onward and upward. Geological history, therefore, if its records in the stratified formations were perfect, ought to show a blending and gradation of epoch with epoch, so that no sharp divisions of its events could be made. But the record of the history has been constantly interrupted: now by upheaval, now by volcanic outbursts, now by depression, now by protracted and extensive denudation. These interruptions serve as natural divisions in the chronicle, and enable the geologist to arrange his history into periods. As the order of succession among stratified rocks was first made out in Europe, and as many of the gaps in that succession were found to be widespread over the European area, the divisions which experience established for that portion of the globe came to be regarded as typical, and the names adopted for them were applied to the rocks of other and far distant regions. This application has brought out the fact that some of the most marked geological breaks in Europe do not exist elsewhere, and, on the other hand, that some portions of the record are much more complete there than in other regions. Hence, while the general similarity of succession may remain, different subdivisions and nomenclature are required as we pass from continent to continent.

The smallest and simplest subdivision of the Geological Record is a stratum, layer, seam or bed. As a rule it is distinguishable by lithological rather than palæontological features. Where a bed, or limited number of beds, is characterised by one or more distinctive fossils, it is termed a zone or horizon, and, as already mentioned, is often known by the name of a typical fossil, as the different zones in the Lias are by their special species of ammonite.[1] Two or more such zones, united by the occurrence in them of a number of the same characteristic species or genera, may be called beds or an assise, as in the "Micraster beds or assise" of the Cretaceous system, which include the zones of *M. cor-testudinarium* and *M. cor-anguinum*. Two or more sets of such connected beds or assises may be termed a group or stage (*étage*). In some cases, where the number of assises in a stage is large, they are grouped into sub-stages (*sous-étages*) or sub-groups. Each sub-stage or sub-group will then consist of several assises, and the stage or group of several sub-stages or sub-groups. A number of groups or stages constitutes a series, section (*Abtheilung*), or formation, and a number of series, sections, or formations may be united into a system.[2]

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[1] Prof. Gaudry estimates the total number of zones in the European geological series at 114. In this calculation the Jurassic system is allowed no fewer than 34 ; the Carboniferous and Permian together, 10 ; and the Cambrian and Silurian together, 20 ('Enchaînements du Monde Animal : Fossiles Primaires,' 1883). Professor Lapworth has recognised 20 distinct graptolite zones in the Cambrian and Silurian systems (*Ann. Mag. Nat. Hist.* ser. 5, vols. iii. iv. v. vi. (1879–80), see especially the last part of his paper in vol. vi. p. 196 *seq.*) See also *postea*, p. 741.

[2] Compare Hébert, *Ann. Sci. Géol.* xi. (1881). The unification of geological nomenclature throughout the world is one of the objects aimed at by the "International Geological Congress," which at its meeting at Bologna recommended the adoption of the following terms, the most comprehensive being placed first:—

Divisions of sedimentary formations.	*Corresponding chronological terms.*
Group.	Era.
System.	Period
Series.	Epoch.
Stage.	Age.

THE GEOLOGICAL RECORD,

OR, ORDER OF SUCCESSION OF THE STRATIFIED FORMATIONS OF THE EARTH'S CRUST.

	Europe.	North America.	India and adjacent regions.	New Zealand.
QUATERNARY OR POST-TERTIARY.	**Recent** and **Prehistoric**—alluvia of rivers, lakes, and seas; peat, shell-beds, &c. Younger raised beaches, kitchen-middens, lake-dwellings, &c. Neolithic and Palæolithic deposits.	Recent.	Recent and Post-tertiary alluvium.	Recent, alluvium, volcanic rocks.
	Pleistocene (Diluvium)—cave deposits, Loess, older valley-gravels and raised beaches. Glacial deposits, consisting of latest moraines, upper boulder-clays and esker drifts, interglacial beds and lower boulder-clays.	Champlain—old terraces (marine, lacustrine, and fluviatile), unstratified drifts, passing down into glacial deposits.	Laterite.	Pleistocene, with *Moa* bones and traces of man, glacial deposits; raised beaches.
TERTIARY OR CAINOZOIC.	**Pliocene**—English Forest-bed group and subdivisions of the Crag; Arnusian and Villafranchian of southern France and northern Italy; Astian of Liguria and southern France; Plaisancian of northern Apennines and southern France; Diestian of Holland and Belgium (older Crag of England); Messinian and Zanclean of Sicily and Italy.	Pliocene—Not certainly recognisable in Eastern States. Loup River group of Upper Missouri.	Upper and middle Sewalik beds. Upper Manchhars of Sind.	Shingle Plains. Lignite and Kereru beds.
	Miocene—not known in Britain; in France, Switzerland, Italy, (3) Tortonian marls underlain by (2) Helvetian sands (Faluns of Touraine), and these by (1) Lhangian sands, marls, and limestones (Orleanais, Sansan, &c.); Bolderian and Anversian of Belgium; Sarmatian overlying Mediterranean stage of Vienna basin; Molasse of Switzerland.	Miocene—Sumpter, Yorktown, (Marylandian, Virginian, Carolinian) of Eastern States, White River beds of Upper Missouri.	Lower Manchhars of Sind.	Upper—Wanganui and Awatere beds. Lower—Maungapakeha and Pareora beds.
	Oligocene—Upper fluvio-marine beds of Isle of Wight; Basalt plateaux of N.W. Europe and Iceland; Rupelian and Tongrian of Belgium, Calcaire de la Beauce, Grès de Fontainebleau, Gypse lacustre, &c.; Brown Coal series of Germany. In France, Belgium, Switzerland, and northern Italy the following subdivisions have been generally adopted: Aquitanian stage; Stampian stage; Tongrian stage, underlain in N. Italy by the Sestian stage.	Oligocene (?)—Vicksburg beds.		
	Eocene—sands and clays of the London and Hampshire basins; Gypsum, Caillasses, Calcaire grossier, &c., of Paris basin; Nummulitic Limestone and Flysch (in part) of Alps and	Eocene—Lignitic sands and clays, Clayborne and Jackson (Alabama) beds of the East—Wah-	Nari group, Kirthar group, Ranikot beds, Nummulitic	Mount Brown and Nummulitic beds—Shelly calcareous sandstones, with abundant

The nomenclature adopted for these subdivisions bears witness to the rapid growth of geology. It is a patchwork in which no uniform system nor language has been adhered to, but where the influences by which the progress of the science has been moulded may be distinctly traced. Some of the earliest names are lithological, and remind us of the fact that mineralogy and petrography preceded geology in the order of birth—Chalk, Oolite, Greensand, Millstone Grit. Others are topographical, and bear witness to the localities where formations were first observed, or are typically developed—Oxfordian, Portlandian, Kimeridgian, Jurassic, Rhætic, Permian, Neocomian. Others are taken from local English provincial names, and remind us of the special debt we owe to William Smith, by whom so many of them were first used—Lias, Gault, Crag, Cornbrash. Others recognise an order of superposition as already established among formations—Old Red Sandstone, New Red Sandstone; while still another class is founded upon numerical considerations—Dyas, Trias. By common consent it is admitted that names taken from the region where a formation or group of rocks is typically developed, are best adapted for general use. Cambrian, Silurian, Devonian, Permian, Jurassic, are of this class, and have been adopted all over the globe.

But, whatever be the name chosen to designate a particular group of strata, it soon comes to be used as a chronological or homotaxial term, apart altogether from the lithological character of the strata to which it is applied. Thus we speak of the Chalk or Cretaceous system, and embrace, under that term, formations which may contain no chalk; and we may describe as Silurian, a series of strata utterly unlike in lithological characters to the formations in the typical Silurian country. In using these terms, we unconsciously adopt the idea of relative date. Hence such a word as Chalk, or Cretaceous, does not so much suggest to the geologist the group of strata so called, as the interval of geological history which these strata represent. He speaks of the Cretaceous, Jurassic, and Cambrian periods, and of the Cretaceous fauna, the

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As equivalents of *Series*, the terms *Section* or *Abtheilung* may be used: as a subdivision of *Stage*, the words *Beds* or *Assise*.

"According to this scheme," Mr. Topley, one of the secretaries, remarks, "we would speak of the Palæozoic Group or Era, the Silurian System or Period, the Ludlow Series or Epoch, and the Aymestry Stage or Age. The term 'formation' raises a difficulty, because this word is used by English geologists in a sense unknown abroad. To bring our nomenclature into conformity with that of other nations it will be necessary to use the word only as descriptive of the mode of formation, or of the material composing the rock. We may speak of the 'Carboniferous Formation' as a group of beds containing coal; but not as a name for a set of rocks apart from the mineral contents. In like manner, we may speak of the 'Chalk Formation,' but not of the 'Cretaceous Formation'" (*Geol. Mag.* 1881, p. 557; *Compte rendu*, 2^{me} *Cong. Géol.* Bologna, 1881). It may be doubted whether the recommendations of any congress, international or other, will be powerful enough to alter the established usages of the language. The term *group* has been so universally employed in English literature for a division subordinate in value to *series* and *system* that the attempt to alter its significance would introduce far more confusion than can possibly arise from its retention in the accustomed sense.

Jurassic flora, the Cambrian trilobites, as if these adjectives denoted simply epochs of geological time.

The Geological Record is classified into five main divisions: (1) Pre-Cambrian, also called Archæan, Azoic (lifeless), Eozoic (dawn of life) or Proterozoic (earliest life); (2) Palæozoic (ancient life) or Primary; (3) Mesozoic (middle life) or Secondary; (4) Cainozoic (recent life) or Tertiary, and (5) Post-Tertiary or Quaternary. The Tertiary and Post-Tertiary are sometimes grouped together as Neozoic (new life). These divisions are further ranged in systems, each system in series, sections, or formations, each formation in groups or stages, and each group in single zones or horizons.[1] The accompanying generalised table exhibits the sequence of the chief subdivisions.

PART I. PRE-CAMBRIAN.

§ i. General Characters.

In the classification of the materials of the earth's crust enunciated by Werner the term "transition rocks" was applied to a large series of stratified formations, which, underlying the well-known fossiliferous or Secondary deposits, and overlying the various crystalline masses which were regarded as the most ancient or Primary part of the earth's surface, were believed to record an intermediate period of terrestrial history, between the time when any such crystalline materials as granite were laid down from a supposed universal ocean and the time when ordinary sediment accumulated and entombed the remains of the earliest animal life. Long after the theoretical considerations that led to its adoption had been proved to be fallacious, this term "transition" continued to maintain its ground as the designation of the most ancient stratified rocks underlying the Old Red Sandstone, and containing the earliest known organic remains. The researches of Murchison and Sedgwick eventually showed that these venerable formations contained a well-marked succession of organic types, whereby, as in the case of the Secondary rocks, so admirably made out by William Smith, they could be grouped into separate systems and formations, and could be identified in all parts of the world. The terms Cambrian and Silurian (which will be explained in later pages) were proposed by these illustrious pioneers to denote the oldest known fossiliferous formations, and soon entirely supplanted the older names "transition" and "grauwacke." The Cambrian system, as now generally understood, includes the lowest series of Primary, or as they are now called, Palæozoic deposits (see *postea*, p. 719).

But it has been well established that, while in some regions the base of the Cambrian system is separated by a strong unconformability from all rocks of older date, in other tracts it can only be defined by an arbitrary line, beneath which lie other still more ancient sedimentary formations.

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[1] On the classification of the Geological Record see Dr. W. T. Blanford, *Geol. Mag.* 1884. Prof. Renevier, *Bull. Soc. Vaud.* xiii. p. 229; *Arch. Sci. Phys. Nat.* xii. (1884) p. 297.

In these primeval deposits there are records of denudation and deposition, of alternate sedimentation and terrestrial movements, of stupendous and prolonged volcanic activity, and of distinct though scanty proofs that plant and animal life had already appeared upon the face of the globe. So far as our knowledge yet goes there is no means of ascertaining the synchronism or homotaxis of these formations in widely separated regions. Fossil evidence entirely fails here as a guide, and mere mineral characters are only reliable within comparatively limited areas. All that can for the present be attempted is to determine the true order of sequence, tectonic relations and general structure of the several distinct formations in each country where they occur, without in the meantime any serious attempt at correlation.

It must further be observed that these oldest stratified rocks have very generally undergone more or less alteration during the numerous terrestrial disturbances of geological history. Lying as they do at the base of the stratified part of the earth's crust, they have shared in the movements by which, during the lapse of geological time, the fossiliferous rocks have been affected. Every intruded mass of igneous rock, every volcanic outburst, every agent of contact or of regional metamorphism had first to pass through them before it could reach the younger rocks above. Hence not only have they usually been dislocated and plicated, but they have been abundantly invaded by intrusive materials of all ages, and their internal structure has frequently been subjected to such mechanical stresses, with accompanying chemical and mineralogical readjustments of their component materials, that they have passed into the condition of schists. In this highly altered state they often cannot be distinguished from still more ancient schists, the true origin of which is not certainly known. In some regions, indeed, where the older sedimentary formations have been greatly disturbed, a gradation may be traced from unmistakable Palæozoic or Mesozoic sediments with recognisable fossils into thoroughly crystalline and foliated schists. Sometimes this transition is doubtless due to an actual extensive metamorphism of the sedimentary rocks, and in these instances there may be no means of separating the schists of which the sedimentary origin is ascertainable from those where it is not. The whole may be Palæozoic or Mesozoic. In other cases, there seems reason to believe that the gradation is rather due to excessive plication, whereby ancient schists and Palæozoic or Mesozoic strata have been so compressed that they agree in direction of strike, and have been so folded that portions of the one series have been enclosed within the other, considerable general metamorphism having at the same time been superinduced upon the whole.

From underneath these oldest sedimentary accumulations there rises to the surface a remarkable assemblage of thoroughly crystalline rocks, which range from amorphous masses such as granite, syenite, diorite, and gabbro, through many varieties of coarse and fine foliated rocks to the most silky schists and phyllites, and which further vary in chemical composition from thoroughly acid materials (granites, felsites, &c.) to basic or even what are called "ultra-basic" compounds (peridotites, Jurassic flora, the Cambrian trilobites, as if these adjectives denoted simply epochs of geological time.

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The infra-position of these crystalline rocks, combined with their prevalent stratified appearance, naturally led to their being regarded as the oldest known formation on which all the later portions of the terrestrial crust rest. But recent observations have proved many gneisses to be originally igneous rocks, sometimes even intrusive, and therefore younger in date than the rocks which they pierce (pp. 186, 615). Where the area in which these ancient mineral masses are exposed is small, and especially where only the gneissic or schistose portion of them is seen, the oldest fossiliferous rocks may lie on them with a strong unconformability. The contrast in such conditions between the stratified conglomerates, sandstones, and shales of the Palæozoic series, and the gnarled crystalline gneisses below them is so striking as to have suggested the idea that in these gneisses we have reached the lowest and earliest part of the earth's crust. Hence arose such names as Fundamental gneiss, Urgneiss or Urgebirge.

No portion of the Geological Record has in recent years been more diligently studied than the crystalline schists, which, underlying the vast pile of fossiliferous systems, have been regarded as the earliest surviving chronicles of the history of the earth. But the problems presented by these rocks are so many and so difficult that comparatively little progress has been made in the endeavour to group them into formations or systems comparable with those of the fossilferous series, and to ascertain the stages of geological history of which they are the memorials. The obstacles to increase of knowledge on this subject arise from the complication and obscurity of the geotectonic relations of the rocks. We have as yet no satisfactory clue to their chronological sequence. They have undergone so many disturbances of their mass, and so many and serious alterations of their internal structure, that it is often quite impossible to be certain of their true sequence. Nothing in the least degree analogous to the evidence of fossils among the sedimentary rocks is here available. Whether eventually a determinable order of appearance among the minerals of these ancient rocks may be ascertained remains still uncertain. If it could be shown that certain minerals, or groups of minerals, came into existence at particular stages in the formation of the crystalline schists, a key might be found to some of the most difficult parts of this branch of geological enquiry. But though such a sequence has often been claimed to exist, no satisfactory proof has yet been adduced that it has been asserted on more than mere local observation. Certainly no general law of mineral sequence in geological times has hitherto been established.[1]

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[1] The late T. S. Hunt was one of the main exponents of the view that the crystalline pre-Cambrian rocks were deposited as chemical sediments in a certain definite order, and that the rocks could be recognised by their mineral characters, and be thereby grouped in their proper order all over the world. See, for example, his essays on "The Taconic Question in Geology," and on "The Origin of the Crystalline Rocks" in vols. i. and ii. of the *Trans. Roy.*

Thus while it is often difficult or impossible to ascertain the original order of succession among the crystalline schists of a particular region, it is even more difficult to form a satisfactory judgment as to the stratigraphical relations of the schists of two detached regions. There is usually no common basis of comparison between them, except similarity of mineral character and structure. But as it can be shown that even in a single area the crystalline schists may sometimes represent the results of many successive operations continuing through a long series of geological periods, it is obvious that the task of correlating these rocks in distinct, and especially in widely separated, areas must be beset with almost insuperable obstacles.

Though in many countries a complete break occurs between the lowest gneisses and the overlying Palæozoic sedimentary formations, there are other regions in which these gneisses are intimately associated with schists, limestones, quartzites, and conglomerates. The real character of this association has been variously interpreted, but on any explanation, it shows that such gneisses cannot be older than certain crystalline masses which may be regarded as probably, if not certainly, of sedimentary origin. Hence, while the inference from one series of sections has been that the gneisses belong to an early condition of the cooling crust of the globe, from another series it has been in favour of these gneisses and their associated sedimentary materials having been formed after the crust was solidified, and after mechanical and chemical sediments had begun to be accumulated.

Taking the widest view of the whole series of pre-Palæozoic rocks, with their vast piles of various sedimentary formations above, and their complex series of crystalline massive and schistose rocks below, we encounter a somewhat serious difficulty in the attempt to group the whole of this varied assemblage of mineral masses under some common generally applicable stratigraphical name. Such a name has usually been held to imply that the rocks which it designates belong to one well-defined portion of the Geological Record. But this implication is one which every geologist who has worked among these ancient rocks would earnestly deprecate, for he has in some measure realised how vast, varied, and long-continued were the geological changes of which they are the memorials. These mutations include many transformations of the earth's surface, many disturbances of its crust, with enormous denudation and sedimentation, comparable with, if not greater than, those which in later ages were repeated again and again, even after the older fossiliferous formations were laid down. So similar have been the results that it is now difficult, or impossible, to discriminate between the more ancient and the more recent operations. To class all the crystalline schists and the great piles of sedimentary and igneous materials into which they seem to pass, by one general name, after the type of "Cambrian," "Silurian," or "Devonian," may be convenient, but in the present state of our knowledge is apt to lead to confusion, by placing together masses which may be of widely different geological ages and of

Soc. Canada. How completely this artificial system breaks down when tested by an appeal to the rocks in the field has been well shown by R. D. Irving, *7th Ann. Rep. U.S. Geol. Survey* (1888), p. 383.

wholly dissimilar origin. Various terms have been proposed for this complex assemblage of rocks, such as Primitive, Proterozoic, Azoic, Agnotozoic or Archæan. But from the data adduced in Book IV. Part VIII. regarding regional metamorphism, the student will understand how full of uncertainty must be the geological age of many areas of crystalline schists. Mere lithological characters afford no perfectly reliable test of relative antiquity. To prove that any region of crystalline schists may be "Primitive," "Azoic," or "Archæan" we must first find these rocks overlain by the oldest fossiliferous formations. Where no evidence of this kind is available, the use of precise terms, which are meant to denote a particular geological era, is undesirable. There seems good reason to believe that the asserted "Archæan" age of many tracts of schistose and granitoid rocks rests on no better basis than mere supposition, and that as the study of regional metamorphism is extended, the so-called "Archæan" areas will be proportionately contracted.[1]

Several distinct systems of mineral masses can be shown in some regions to exist beneath the base of the Palæozoic formations, differing so greatly in petrological characters, in tectonic relations, and probably also in mode of formation, that they cannot, without a very unnatural union, be arranged in one definite stratigraphical series. For the present it seems to me least objectionable to adopt some vague general term which nevertheless expresses the only homotaxial relation about which there can be no doubt. For this purpose the designation "Pre-Cambrian," already in use, seems suitable. The rocks which I would embrace under this epithet may include a number of separate systems or formations which have little or nothing in common, save the fact that they are all older than the base of the Cambrian rocks. Until our knowledge of these ancient masses is much more extensive and precise than it is at present I think it would be of advantage to avoid the adoption of any general terminology that would involve assumptions as to their definite place and sequence in the geological record, their mode of origin, their relation to the history of plant and animal life, or their identification in different countries.

As an illustration of the danger of such assumptions, I may refer to the history of the investigation of the Laurentian rocks of Canada. From the early observations of Sir W. Logan and Mr. Alexander Murray these rocks came to be regarded as types of the oldest gneisses of the globe. They were looked upon as probably metamorphosed marine sediments that had formed the solid platform on which the whole series of fossiliferous systems of North America had been deposited. The name Laurentian applied to them was transferred to similar rock-masses in other parts of the globe, and came to be accepted as the designation of the oldest known zone in the crust of the earth. But eventually it was discovered by Mr. Lawson that some part, at least, of the Laurentian gneiss is essentially of igneous not of sedimentary origin, and is actually intrusive into what are undoubtedly sedimentary strata. It could not, therefore, itself as a whole be the oldest rock; and all the generalisations and identifications founded on its supposed position fell to the ground. The term Laurentian cannot henceforth have more than a local significance. It serves to designate certain ancient crystalline rocks of Canada, but a geologist would not now employ it to denote any of the rocks of another region, even though they might present similar general lithological characters. We must in the meanwhile be content to restrict the application of such names to the regions in which they originated. There will be much less impediment to the progress of investigation by the multiplication of local names than by the attempt to force identifications for which there is no satisfactory basis. Each country will have its own terminology for pre-Cambrian formations, until some way is discovered of correlating these formations in different parts of the globe.

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[1] Dr. Barrois thus expresses himself on this subject : "A great number of the rocks considered to be Archæan in Brittany are only metamorphosed Cambrian or Silurian rocks, having merely the facies of primitive rocks. We do not think that Brittany can be the only region where this is the case ; on the contrary, it seems to us probable that the Palæozoic formations are destined to spread more and more over geological maps, at the expense of the 'primitive formations,' by assuming gneissic and schistose modifications."—*Ann. Soc. Géol. Nord.* xi. (1884), p. 139 (*ante*, p. 612 *et seq.*)

Although where the stratigraphical succession is most complete the gneisses that rise from under the oldest sedimentary rocks have been found to pierce these rocks, and thus to be of later date; yet in most regions no such proof of posteriority is to be seen. The coarse banded gneisses are usually the foundations on which the stratified fossiliferous formations unconformably rest. There is thus an obvious advantage in treating these gneisses first in an account of pre-Cambrian rocks. I shall here follow this arrangement, and reserve for a later section a description of the sedimentary and igneous formations which intervene between the gneisses and the base of the Cambrian system.

1. *The lowest gneisses and schists.*

It has often been remarked that one of the most singular features about the oldest known crystalline rocks is the sameness of their general mineral characters in all parts of the earth. Sedimentary formations constantly vary from country to country, but when we descend beneath their lowest members we come upon a wholly different group of rocks which retain with remarkable uniformity one general type of structure and composition. These rocks include massive materials such as granite, syenite, gabbro, diorite, and hornblende-rock. But even in these a tendency to a schistose arrangment can usually be observed. By far the most generally prevalent structure is a more or less definite foliation. In the coarse varieties it is marked by alternate bands of distinct mineral characters, orthoclase, plagioclase (commonly an acid variety), quartz, hornblende and mica (white and black) being universally conspicuous. Such rudely foliated rocks are known as coarsely-banded gneisses, and offer gradations into masses which cannot be distinguished from ordinary eruptive material. The banding is sometimes strongly marked by the separation of the more silicated from the less silicated minerals, as where layers of felspar or of quartz alternate with others of hornblende, pyroxene or biotite.

While the foliated structure and the arrangement of the minerals in parallel bands gives a bedded aspect to these rocks, the resemblance of this structure to the true bedding of detrital materials is probably more apparent than real. A little examination shows that the layers are not persistent, that they cross each other, and that portions of one may be entirely separated and enclosed within another. Whatever may have been their origin they have certainly undergone enormous mechanical compression and deformation. They have been plicated, rolled out, dislocated, and crumpled again and again. Hence, though for short distances it is possible to separate out layers or bosses of felspathic, hornblendic, pyroxenic, peridotitic, or serpentinous composition from the general body of gneiss, the geologist who tries to fix definite stratigraphical horizons by this means soon abandons the attempt in despair, and comes to the conclusion that no sequence of a trustworthy nature can be established in the body of the gneiss itself.

From the coarsest gneisses gradations may be traced to fine silky schists; and this not only on a large scale in tracts capable of being delineated on a map, but on so small a scale as to be illustrated even in hand-specimens. Such transitions seem to arise from the different effects of mechanical deformation on materials that offered considerable differences in lithological composition and structure. Fine talcose schists, for example, can be traced to original peridotites; hornblendic and actinolitic schists to such rocks as gabbro, diorite, or dolerite.

In the older accounts of these rocks the gneisses are described as passing into or alternating with a wholly different type of rocks, among which may be included limestone (sometimes strongly graphitic), dolomite, quartzite, graphite-schist, mica-schist, and other varieties of schistose material. This apparent gradation was believed to mark an original transition of the sediment out of which the gneiss was thought to have been formed into the calcareous, argillaceous, or carbonaceous sediment, which was the earliest condition of the associated limestones and schists. It was thus looked upon as evidence that the whole crystalline series represented, in a metamorphosed state, an ancient accumulation of sedimentary materials. The existence even of organic remains in the limestone was insisted upon, and the so-called *Eozoon* was cited as the most ancient relic of animal life.[1] But there is now every reason to believe such gradations to be generally deceptive. As a result of the enormous mechanical compression and deformation which these ancient rocks have undergone, igneous and aqueous materials have been so plicated and crushed together and have undergone such profound metamorphism, that it is sometimes hardly possible to trace a boundary between them. There seems no reason to look upon the limestones, argillites, quartzites, and schists as other than intensely altered sediments, which in theory, if not in actual practice on the ground, must be separated from the gneisses.

Among the various theories which have been proposed to account for the genesis of the lowest gneisses and schists, three deserve particular mention here. (1) These rocks are by some geologists believed to be a portion of the original crust which solidified on the surface of the globe. (2) They are by others held to be ancient sedimentary rocks in a metamorphosed condition, and in some parts so changed as to have been actually melted and converted into intrusive material. (3) They are believed by yet another class of observers to be essentially eruptive rocks, and to be comparable with the deeper seated or plutonic portions of such igneous rocks as may be seen to traverse the earth's crust.

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[1] See on this subject *postea*, p. 694, and authorities there cited.

(1) From the ubiquity of their appearance, the persistence of their striking lithological characters, and especially the curious apparent blending in them of the igneous and sedimentary types of structure, the idea not unnaturally arose that the lowest crystalline rocks represent the first crust that formed on the surface of the globe.[1] These rocks have been supposed to include some of the early surfaces of consolidation of the molten globe, and some of the first sediments that were thrown down from the hot ocean which eventually condensed upon the planet. Such a speculative view of their origin may seem not incredible in regions where these ancient crystalline rocks are covered unconformably by the oldest Palæozoic formations, from which they are marked off by so striking a contrast of structure and composition, and to which they have contributed so vast an amount of detrital material. But it must be tested by the evidence of the rocks themselves, not only where the geological record is confessedly incomplete, but where it is comparatively full. Nowhere among the lowest gneisses is any structure observable which can be compared with the superficial portion of a lava that cooled at the surface. On the contrary the analogies they furnish are with deep-seated and slowly-cooled sills and bosses. The supposed intercalation and alternation of limestone and other presumably sedimentary materials in the old gneisses are probably all deceptive. In some regions they can be shown to be so, and it can there be demonstrated that the gneisses are really eruptive rocks which pierce the adjacent sedimentary or schistose masses, and are thus of younger age than these. If this relation can be clearly established in regions where the evidence is fullest, it is obviously safe to infer that a similar relation might be discoverable if the geological record were more complete, even in those parts of the world where the break between the lowest gneisses and the Palæozoic formations seems to be most pronounced. At least the possibility that such may be the case should put us on our guard against adopting any crude speculation about the original crust of the earth.

The present condition of these ancient rocks differs much from that which they originally possessed. In particular they have undergone enormous mechanical deformation, have been to a large extent crushed and re-crystallized, and have acquired a marked schistose structure. But in every large region where they are developed we may obtain evidence to connect them with plutonic intrusions, not with superficial consolidation, and to show that many of their essential details of structure may be paralleled among much later crystalline schists produced from the metamorphism of Palæozoic sediments and igneous rocks.

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[1] See Credner's "Geologie," vi. *b.* Die Fundamental Formation; Erstarrungskruste. Compare also Rosenbusch, *Neues Jahrb.* 1889, vol. ii. p. 81.

(2) That the lowest gneisses of Canada and other regions are metamorphosed sedimentary rocks was believed by probably most geologists until only a few years ago. But the increased attention which has been given to the study of the subject since Professor Lehmann's great work on the Saxon gneisses appeared in 1884, has led to so complete a revolution of opinion that this belief, at least in its original form, is now almost wholly abandoned. Those who still hold it in a modified shape recognise that the original sediments must have differed considerably from those of any recognisably sedimentary formation, and were probably deposited under peculiar conditions. They admit that these rocks have undergone extreme metamorphism, and that the alteration of them has been carried so far as to reduce them in some places to an amorphous crystalline condition which cannot be distinguished from that of normal eruptive material. It has been maintained, indeed, that the Laurentian gneisses of Canada have been produced by the actual fusion of the older sedimentary pre-Cambrian formations and the absorption of these rocks into the general magma of eruptive material which now appears as gneiss.[1] The intrusive character of some of the gneiss, which might be regarded as proof of its really igneous origin, is accounted for by what is called an "aquo-igneous fusion" of some parts of the sedimentary rocks and their intrusion into less completely metamorphosed portions of the series.

(3) Probably the great majority of geologists now adopt in some form the third opinion, that the oldest or so-called "Archæan" gneisses are essentially eruptive rocks, and that they should be compared with the larger and more deeply-seated bosses of intrusive material now visible on the earth's surface. Whether they were portions of an original molten magma protruded from beneath the crust, or were produced by a re-fusion of already solidified parts of that crust or of ancient sedimentary accumulations laid down upon it, must be matter of speculation. In the gathering of actual fact we cannot go beyond their character as eruptive rocks, which is the earliest condition to which they can be traced, and we must consequently place them in the same great series as all the later eruptive materials with which geology has to deal. It is quite true that they have been profoundly modified since their original extrusion, but traces of their original character as masses of mobile, slowly crystallizing and segregating material have not been entirely effaced.

Looking at the gneisses as a whole, with their various accompaniments, we find them to form a complex assemblage of crystalline rocks which, though generally presenting a foliated structure, pass occasionally into the amorphous condition of ordinary eruptive rocks. In composition they range from granite at the one end to peridotites and serpentines at the other. Hand-specimens of these rocks in their amorphous or unfoliated condition do not differ in any essential feature from the material of ordinary intrusive bosses in later portions of the terrestrial crust, and the same similarity of structure is borne out when thin slices are placed under the microscope.

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[1] A. C. Lawson, *Annual Report Canadian Geol. Surv.* 1887.

Perhaps the most convincing proof of the really eruptive nature of the gneisses is to be found in those tracts where they have undergone least disturbance, and where therefore the way in which they traverse the adjacent rocks can be distinctly perceived. They are there seen to cross many successive zones of sedimentary material, to send out veins and protrusions, and to enclose portions of the adjacent rocks, while at the same time the surrounding masses present many of the familiar features of contact-metamorphism. Sections where these phenomena can be satisfactorily observed are no doubt comparatively rare, for in general the rocks have been so crushed and re-crystallized that their original relations have been destroyed. It is in consequence of these subsequent movements that so much difficulty has been found in determining the igneous nature of the gneisses and their intrusive character with reference to the rocks adjacent to them. The abundant veins which, as in ordinary granite bosses, proceeded from the original gneiss have been compressed into long parallel bands which seem to alternate with the schists among which they were injected, while portions of the surrounding rock enclosed within the gneiss have had a foliation superinduced upon them parallel to that of these bands. Any one who first studied the older rocks where such structures are visible might easily be deceived into the belief that these alternations of parallel strips of gneiss and schist, or gneiss and limestone, really represented a continuous sequence of sedimentary material. Nor would he readily perceive his mistake until he could trace the junction-line into some tract where, by cessation of the deformation, the original relation of the two groups of rocks could be observed.[1]

It is not difficult to obtain conclusive proof that in the complex assemblage of rocks constituting the lowest gneiss there are not only differences of composition and structure, but also differences of relative age. Some portions of the series can be distinctly seen to have been intruded into others. True dykes can be traced among them both of acid and basic composition. In the north-west of Scotland, for example, the general body of gneiss is traversed by a multiplicity of dykes, cutting across the oldest foliation of the gneiss in a general north-westerly direction. A detailed study of such an area reveals the fact that the fundamental rocks represent a prolonged series of igneous protrusions. As this complicated mass of eruptive material has subsequently undergone profound alteration by dynamo-metamorphism, the difficulties in unravelling its history need cause no surprise.

Leaving out of account the dykes which undoubtedly mark later injections of igneous material, and confining our attention to the general mass of gneiss in its variations from an amorphous or granitoid condition through the coarse banded varieties to the finer schistose types, we may pursue the history of these puzzling rocks by comparing them with the larger intrusive bosses and sills that have accompanied the volcanic eruptions of all geological periods. In these deep-seated and slowly cooled masses of igneous material, as has already been pointed out (p. 580), we may frequently observe evidence of the segregation of the component minerals in bands or irregular patches. Such a segregation seems to have taken place sometimes after the erupted rock had come to rest, sometimes while it was still in movement. In the latter case the layers of separated materials may sometimes have been dragged forward so as to acquire a somewhat banded or streaky structure. How far the characteristic arrangements of the minerals in the coarse banded gneisses may have arisen from a process of this kind in the consolidation of originally eruptive materials, remains still an open question, though the progress of research favours the idea that such has really been to a large extent their source.[1]

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[1] See A. C. Lawson, *Bull. Geol. Soc. Amer.* i. (1890) p. 184.

It is certain, however, that, besides the original banded and probably segregated structure, the gneisses, as the result of much mechanical deformation, have had other and later structures superinduced upon them, sometimes at successive periods of disturbance. The most massive granitoid rocks have thus been crushed down under great strain, and have re-crystallized as fine granulitic gneiss or mica-schist. Epidiorites and amphibolites have by a similar process been converted into hornblende-schists. In these cases the reconstructed rocks usually exhibit a finely schistose structure, quite distinct from that of the parent mass, but with no markedly banded arrangement. Occasionally, however, in the re-crystallization of the materials, segregation into more or less definite layers or centres has come into play, so that in this obviously secondary arrangement a certain resemblance may be traced, though on a small scale, to the much coarser bands in the earliest remaining condition of the oldest gneisses.

There is yet another source of difficulty in judging of the relative age and origin of various structures among the crystalline schists. As has already been pointed out (p. 604), it is now well established that granite, besides breaking through the old rocks and forming huge bosses, as well as abundant veins among them, has sometimes been introduced into their substance in such a way that they seem to be permeated by the granitic material. Minute layers and lenticles of this material, quite uncrushed, may be traced between the foliation planes of granulitic gneisses and different schists. But where subsequent movement has crushed and drawn out these intercalated layers, younger gneiss is produced that simulates with extraordinary closeness some aspects of the most ancient and, so to say, original gneisses.[2] This transformation appears to take place even among schists that can be shown to have been originally sedimentary rocks. So that by a new pathway of inquiry we are brought once more to the old doctrine of the cycle of change through which the materials of the earth's crust pass. The most ancient gneisses exposed to disintegration on the earth's surface have furnished materials for the formation of sedimentary deposits, which, after being deeply buried within the earth's crust, crushed, plicated, and permeated with granitic material, present once more the aspect of the old gneisses from which they were in the first instance derived.

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[1] This inference applies more particularly to the coarsely banded gneisses where the individual layers, consisting in great part of different minerals, resemble some of the segregation bands in eruptive masses (p. 615). There can be little doubt that, as already remarked, the efficacy of mechanical deformation as a factor in the production of gneisses has been pushed too far. It will account for the crushed granulitic and schistose condition, but hardly for the coarsely banded structure, where the layers consist of very different mineral aggregates.

[2] See observations of J. Horne in *Geological Survey Report*, Report of the Science and Art Department for 1892.

It is only when the complex tectonic relations of the several masses composing the oldest crystalline rocks are closely studied that we can adequately realise how hopeless would be the attempt to establish anything of the nature of a stratigraphical sequence among them. Where different eruptive materials present proofs of successive intrusion, we have indeed a clue to their relative age; but such evidence carries us but a small way. The gneisses where obviously intrusive are indisputably of eruptive origin, but they alternate with finely schistose bands which sometimes seem to cut them. The bedding or banding of the rocks affords no guide whatever as to sequence. It has been so folded and crumpled that even if it represented original stratification it could probably never be unravelled. But there is every reason to believe that it bears no real analogy to stratification. It may sometimes represent, as already stated, layers of segregation and flow-structure in an original igneous magma, at other times planes of movement in the crushing of already consolidated material. But whatever may have been its origin, it remains now in an inextricable complexity. Here and there, indeed, for short distances some well-marked band of rock may be traced, but the various rock-masses generally succeed each other in so rapid and tumultuous a manner as to defy the efforts of the field-geologist who would patiently map them.

As a rule, only where the earliest type of gneiss has been invaded by subsequently intruded masses can a successful attempt be made to disentangle the confused structure. Successive systems of dykes may thus be traced, and evidence may be obtained that powerful dynamic stresses affected the rocks between some of these intrusions. The dykes have sometimes been crushed, plicated, and disrupted until they have been reduced to isolated patches of schist irregularly distributed among the reconstructed gneiss. And through these involved and complicated masses newer groups of dykes have risen, to be again subjected to mechanical deformation.

The question may occur to the student whether this complex system of evidently plutonic igneous rocks was ever connected with any superficial volcanic activity. No such connection has yet been definitely ascertained, but it may be regarded as highly probable. If the most ancient gneisses with their dykes and bosses were the deep-seated portions of the successive uprisings of the igneous magma which culminated in volcanic eruptions, we may hope eventually to discover some trace of the materials that were thrown out to the surface and accumulated there. In some of the overlying pre-Cambrian masses of sedimentary rocks abundant lavas, tuffs, and agglomerates have been found, indicating the outpouring of volcanic material at the surface during the deposition of these sediments. The vast scale of these volcanic eruptions may be inferred from the fact that in the Lake Superior region the accumulated materials discharged at the surface attained a thickness which has been estimated at more than six and a half miles. It may be eventually discovered that some of these superficial manifestations of volcanic action have been connected with bosses, sills, or dykes that form part of the body of the gneiss below.

It must be confessed that much detailed work among the lower gneisses in all parts of the world is needed before the many problems which they present are solved. But the following conclusions regarding them may now be regarded as certain:—these rocks are in the main various forms of original eruptive material, ranging from highly acid to highly basic; they form in general a complex mass belonging to successive periods of extrusion; some of their coarse structures are probably due to a process of segregation in still fluid or mobile, probably molten, material consolidating below the surface; their granulitized and schistose characters, and their folded and crumpled structures point to subsequent intense crushing and deformation; their apparent alternations with limestone and other rocks, which are probably of sedimentary origin, are deceptive, indicating no real continuity of formation, but pointing to the intrusive nature of the gneiss.

2. *Pre-Cambrian sedimentary and volcanic groups.*

In different parts of the world enormous masses of rock are now known to intervene between the oldest or "Archæan" gneisses, and the bottom of the fossiliferous series of formations. It was in Canada that these rocks were first studied. Logan and Murray grouped them under the general name of Huronian, and they were believed to fill up the gap between the Laurentian gneiss on the one hand, and the Potsdam sandstone or base of the fossiliferous series on the other. Later more detailed study of these rocks in Canada and the adjoining regions of the United States has shown them to possess even a greater importance than their original discoverers imagined, for they have been found to consist of several distinct groups or systems, attaining a vast thickness and presenting a record of stupendous disturbances, denudations and depositions of sediment, together with memorials of extensive and prolonged volcanic action. In the higher members of these sedimentary deposits, distinct remains of animal life have in several regions been found. There is thus opened out the possibility of the ultimate discovery of a series of fossiliferous formations even below the base of the Palæozoic series.

Where metamorphism has not interfered with the recognition of their original characters, these ancient sedimentary rocks present no structural feature to distinguish them from the detrital accumulations of higher parts of the geological record. They consist of clays and muds hardened into shales and slates, of sands compacted into sandstones and quartzites, of gravels and shingles solidified into conglomerates. These rocks prove beyond question that the processes of denudation and deposition were already in full operation with results exactly comparable to those of Palæozoic and later time.

Few parts of the stratified crust of the earth present greater interest than these earliest remaining sediments. As the geologist lingers among them, fascinated by their antiquity and by the stubbornness with which they have shrouded their secrets from his anxious scrutiny, he can sometimes scarcely believe that they belong to so remote a part of the earth's history as they can be assuredly proved to do. The shales are often not more venerable in appearance than those of Cambrian or Silurian time, and show as clearly as these do their alternations of finer and coarser sediment. The sandstones display their false-bedding as distinctly as any younger rock, and one can make out the shifting character of the currents and the prevalent direction from which they brought the sand. The conglomerates in their well-rounded fragments tell as distinctly as the shingle of a modern beach of the waste of a land-surface and the pounding action of waves along a shore.

Not only are these structural details precisely similar to those of younger detrital rocks, but we may here and there detect the remains of the pre-Cambrian topography from which these primeval sediments were derived, and on which they were deposited. Hills and valleys, lines of cliff and crag, rocky slopes and undulating hollows have been revealed by the slow denudation of the pre-Cambrian strata under which these features were gradually buried. To this day so marvellously has this early land-surface been preserved under its mantle of sediment during the long course of geological time, that even yet we may trace its successive shore-lines as it gradually settled down beneath the waters in which its detritus gathered. We may follow its promontories and bays and mark how one by one they were finally submerged and entombed beneath their own waste.[1]

But these ancient stratified formations do not consist merely of clastic sediments. They include important masses of limestone and dolomite, sometimes highly crystalline, but elsewhere assuming much of the aspect of ordinary grey compact Palæozoic limestone. Sometimes they contain a considerable amount of graphite, and some of the shales are highly carbonaceous. In other places they are banded with layers and seams or nodules of chert, in a manner closely similar to that in which the Carboniferous Limestone of Western Europe contains its siliceous material. Sometimes the chert bands are as much as forty-five feet thick. The general character of these mingled carbonaceous, calcareous and siliceous masses at once reminds the observer of rocks which have undoubtedly been formed by the agency of organic life. Moreover there occur extensive deposits of iron-carbonate associated like the limestone with chert, and again recalling the results of the co-operation of plant and animal life. The large amount of carbon in some of the shales, points likewise in the same direction.

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[1] These features are admirably displayed in Ross-shire, N.W. Scotland, where the Lewisian gneiss, carved into hills and valleys, has been buried under the Torridon Sandstone (*postea*, p. 705).

It must be confessed, however, that actual traces of recognisable organic forms have only been found in a few places. Various more or less determinable patelloid or discinoid shells, fragments of what appear to have been trilobites (like *Olenellus*, *Olenoides* or *Paradoxides*), small and rather obscure forms like *Hyolithes*, and others like *Stromatopora*, indicate a low fauna somewhat like that of the Cambrian system above.[1] Most of these fossils have been detected by Mr. Walcott below the *Olenellus* zone or base of the Cambrian rocks in the Grand Cañon of the Colorado. In the Animikie district of Lake Superior, fossil tracks and shells like *Lingula*, and some obscure forms like trilobites, have also been met with. More recently Dr. Barrois has traced a band of graphitic quartzite for a long way in the gneiss of Brittany, and has detected in it the presence of radiolarians, belonging to their most primitive group, the Monosphæridæ.[2]

Reference may be made here to the controversy regarding the true nature of certain curious aggregates of calcite and serpentine, which were found many years ago in some of the limestones associated with the lower or Laurentian gneisses of Canada. These minerals were found to be arranged in alternate layers, the calcite forming the main framework of the substance, with the serpentine (sometimes loganite, pyroxene, &c.) disposed in thin, wavy, inconstant layers, as if filling up flattened cavities in the calcareous mass. So different from any ordinary mineral segregation with which he was acquainted did this arrangement appear to Logan, that he was led to regard the substance as probably of organic origin.[3] This opinion was adopted, and the structure of the supposed fossil was worked out in detail by Sir J. W. Dawson of Montreal,[4] who pronounced the organism to be the remains of a massive foraminifer which he called *Eozoon*, and which he believed must have grown in large thick sheets over the sea-bottom. This view was likewise adopted by the late Dr. W. B. Carpenter,[5] who, from additional and better specimens, described a system of internal canals having the characters of those in true foraminiferal structures. Other observers, however, notably Professors King and Rowney of Galway,[6] maintained that the "canal-system" is not of organic but of mineral origin, having arisen in many cases "from the wasting action of carbonated solutions on clotules of 'flocculite' or, it may be, saponite—a disintegrated variety of serpentine, and in others from a similar action on crystalloids of malacolite. In both cases," according to Professor King, "there are produced residual 'figures of corrosion' or arborescent configurations, having often a regular disposition." The regularity of these forms is attributed by Messrs. King and Rowney to their having been determined by a mineral cleavage.[1] Professor Möbius of Kiel[2] also opposed the organic nature of *Eozoon*, maintaining that the supposed canals and passages are merely infiltration veinings of serpentine in the calcite. In some cases, however, the "canal-system" is not filled with serpentine but with dolomite, which seems to prove that the cavities must have existed before either dolomite or serpentine was introduced into the substance. It may be admitted that no structure precisely similar to that of some of the specimens of *Eozoon* has yet been discovered in the mineral kingdom.[3] But it must also be conceded that the chances against the occurrence of any organism in rocks of such antiquity, and which have been so disturbed and mineralized, are so great that nothing but the clearest evidence of a structure which cannot be other than organic should be admitted in proof. If any mineral structure could be appealed to, as so approximately similar as to make it possible that even the most characteristic forms of *Eozoon* might be due to some kind of mineral growth, the question would be most logically settled in a sense adverse to the organic nature of the substance.[4]

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[1] C. D. Walcott, *10th Ann. Rep. U.S. Geol. Surv.* 1890, p. 552.

[2] *Compt. rend.* 8th August 1892.

[3] *Rep. Geol. Surv. Canada*, 1858. *Amer. Journ. Sci.* xxxvii. (1864), p. 272. *Q. J. Geol. Soc.* xxi. (1865) p. 45. Harrington's 'Life of Sir W. E. Logan,' 1883, pp. 365-378.

[4] *Q. J. Geol. Soc.* xxi. (1865) p. 51; xxiii. (1867) p. 257. See also his 'Acadian Geology,' 2nd edit., 'Dawn of Life,' 1875, and 'Notes on Specimens of Eozoon Canadense,' Montreal, 1888.

[5] *Proc. Roy. Soc.* 1864, p. 545. *Q. J. Geol. Soc.* xxi. (1865) p. 59; xxii. (1866) p. 219.

[6] *Quart. Journ. Geol. Soc.* xxii. (1866) p. 185.

The opinion of the organic nature of *Eozoon* has been supposed to receive support from the large quantity of graphite found throughout the older rocks of Canada and the northern parts of the United States. This mineral occurs partly in veins, but chiefly disseminated in scales and laminæ in the limestones and as independent layers. Sir J. W. Dawson estimates the aggregate thickness of it in one band of limestone in the Ottawa district as not less than from 20 to 30 feet, and he thinks it is hardly an exaggeration to say that there is as much carbon in the "Laurentian" as in equivalent areas of the Carboniferous system. He compares some of the pure bands of graphite to beds of coal, and maintains that no other source for their origin can be imagined than the decomposition of carbon-dioxide by living plants.[1]

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[1] Prof. W. King, *Geol. Mag.* 1883, p. 47. See the views of these writers, summarised in their work, 'An old Chapter in the Geological Record with a new Interpretation,' London, 1881, where a full bibliography will be found.

[2] 'Palæontographica,' xxv. p. 175; *Nature*, xx. p. 272. See replies by Carpenter and Dawson, *Nature*, xx. p. 328. *Amer. Journ. Sci.* (3) xvii. p. 196; also *Amer. Journ. Sci.* (3) xviii. p. 117. See also A. G. Nathorst, *Neues Jahrb.* 1892, i. p. 169.

[3] The nearest resemblance to the "canal-system" of *Eozoon* which I have seen in any undoubtedly mere mineral aggregate is in the structure known as micropegmatite, where, in the intergrowth of quartz and orthoclase, arborescent divergent tube-like ramifications of the one mineral are enclosed within the other (see Fig. 5). Mr. Rudler, who called my attention to the resemblance, showed me a remarkable micropegmatite, brought from the Desert of Sinai by Professor Hull, in which the Eozoonal arrangement is at once suggested.

[4] Whitney and Wadsworth in their 'Azoic System' (*Bull. Mus. Comp. Zool. Harvard*, 1884, pp. 528-548) give a summary of the controversy, and decide against the organic origin of *Eozoon*. From the zoological side also Rœmer and Zittel decline to receive Eozoon as an organism. In the pre-Cambrian rocks of Bohemia and Bavaria specimens were some years ago obtained showing a structure like that of the Canadian Eozoon. They were accordingly described as of organic origin, under the respective names of *Eozoon bohemicum* and *E. bavaricum*. But their true mineral nature appears to be now generally admitted. The original 'Tudor specimen' of Eozoon figured by Dawson has recently been re-examined by Mr. J. W. Gregory, who decides against its organic origin. *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 348.

An important and interesting feature of the pre-Cambrian rocks is the occurrence among them of abundant proofs of extensive and long-continued volcanic action. Sheets of lava having an aggregate thickness of many thousand feet are interstratified with coarse and thick volcanic conglomerates and tuffs. The eruptive rocks include both basic and acid varieties, for among them are found diabases, melaphyres (often highly amygdaloidal), porphyrite, gabbro, quartzless and quartziferous porphyry, rhyolitic felsite, augite-syenite, and granite. Some further details regarding these masses will be given in subsequent pages. In the Lake Superior region the amygdaloidal diabases and the conglomerates are largely impregnated with native copper.

While in some regions the original characters of pre-Cambrian rocks, sedimentary and eruptive, are as easily determinable as those of any ordinary Palæozoic series, in others they have been more or less effaced by subsequent geological revolutions. Gradations can sometimes be traced, as in the Penokee district of Wisconsin, from greywackes and slates through every stage of increasing metamorphism into mica-schists which present every appearance of complete original crystallization.[2] The limestones have passed into the condition of marbles; the iron ores, probably originally carbonates, have become oxidized into limonite, hæmatite and magnetite, while the ore has been concentrated into separate masses. The "greenstones" have passed into the condition of true schists.[3] Some of these metamorphosed areas present so many points of resemblance to the lower gneisses already described that it is not at all surprising that they should have been confounded, and that their true relations should only have been made out after much controversy and long-continued detailed study.

A great deal of discussion has arisen as to the true relations of these pre-Cambrian stratified and eruptive rocks to the coarse-crystalline banded gneisses above described. In some sections a complete and strong unconformability occurs between the two series, and no doubt can there exist as to the enormous break that separates them. In other regions, however, the lower gneisses are so involved with schists, limestones, and conglomerates that no satisfactory separation of them has been made, while in some places the gneiss actually crosses these rocks intrusively. Each country or district may present its own phase of the problem. At present we have no means of determining the true correlation of the pre-Cambrian rocks in separate and especially in distant areas. If we admit that the lowest gneisses with their accompaniments form an eruptive assemblage of which the component portions may belong to widely different periods of time, it is quite conceivable that a certain group of sedimentary formations may be found in one district to lie unconformably on these gneisses, and in another to be pierced by some of their younger members.

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[1] But compare the advocacy of an opposite opinion by Whitney and Wadsworth, 'Azoic System,' p. 539.

[2] R. D. Irving and C. R. Van Hose, *10th Ann. Rep. U.S. Geol. Surv.* 1890, p. 434.

[3] G. H. Williams, *Bull. U.S. Geol. Surv.* No. 62, 1890.

There is likewise some difficulty in fixing the upper limit of the pre-Cambrian formations. Where the Cambrian rocks lie on them unconformably the obvious stratigraphical break forms a convenient line of division. But in some countries a thick mass of conformable sedimentary rocks underlies the *Olenellus*-zone which has been taken as the base of the Cambrian system, and in these instances the line of separation becomes entirely arbitrary. Sections of this nature are of great value, inasmuch as they impress upon the geologist that the artificial character of the divisions by which he classes the geological record is not confined to the fossiliferous formations, but marks also those of the pre-Cambrian series. Unconformabilities, even where wide-spread, cannot be regarded as universal phenomena, and though of infinite service in classification, should be employed with the full consciousness that the blanks which they represent do not indicate any world-wide interruption of geological continuity, but may at any moment be filled up by the evidence of more complete sections.

With regard to the comparative value of the pre-Cambrian rocks in the chronology of geological history no precise statement can be made. But various circumstances show that they must represent an enormous period of time. We shall see in succeeding pages that from the general character of the Cambrian fauna it must be regarded as certain that life had existed on the earth for a long series of ages before that fauna appeared, in order that such well-advanced grades of organisation should then have been reached. One of the most interesting chapters of geological history would be supplied if some adequate account could be given of the stages of this long pre-Cambrian evolution.

But the mere thickness and variety of the pre-Cambrian formations, together with their unconformabilities and other structural features, suffice to prove that they represent an enormous chronological interval. In North America, where, so far as at present known, they are most extensively developed, they are estimated to attain a thickness of more than 65,000 feet, or upwards of twelve miles, and have been regarded there as chronologically quite equal to the whole of the rest of the geological record. Even when we eliminate the bedded volcanic rocks from the computation and reduce the remaining sedimentary series to the lowest allowable dimensions, an enormous mass of stratified material remains, which, even if it had been uninterruptedly deposited, would have required a period of time comparable to probably more than that taken by the whole of the Palæozoic systems. But we know that the deposition was not continuous. Both in North America and in Europe there is clear evidence from marked unconformabilities that it was broken by epochs of upheaval and by long periods of extensive denudation. It is evident, therefore, that we must assign to the records of pre Cambrian time a far more important chronological value than has generally been apportioned to them.

If, as already stated, it is impossible in the present state of science to find any satisfactory basis for the correlation of the oldest gneisses in distant and disconnected regions, it is not more practicable to establish a basis of correlation for the pre-Cambrian stratified formations. The evidence of fossils hardly as yet exists, and mere lithological characters are in such circumstances of little value. All that can be done at present is to work out the succession of rocks in each well-defined geographical and geological area, giving local names to the stratigraphical groups or systems that may be established, and trusting to future research for some method of possibly ascertaining the parallelism of these divisions in different parts of the world. Hence in the following summary of the characters of the pre-Cambrian rocks in the Old World and in the New no attempt will be made to adopt any general terminology, but in each country the names and divisions adopted there will be given.

§ ii. Local Development.

Britain.—Much attention has been given in recent years to the pre-Cambrian rocks of the British Isles and a voluminous literature has arisen concerning them. Rocks, however, have been claimed as pre-Cambrian which are certainly eruptive masses of later date than parts of the Lower Silurian series. Others have been assigned to a similar position, though their relations to the older Palæozoic rocks cannot be seen; while others again cannot properly be disjoined from the lower portion of the Cambrian system. In the confusion which has thus been introduced it will be most satisfactory to restrict attention to those rocks and areas about the true relations of which there appears to be least room for dispute.

In no part of the European area are rocks of pre-Cambrian age more admirably displayed than in the north-west of Scotland. Their position there, previously indicated by Macculloch[1] and Hay Cunningham,[2] was first definitely established by Murchison,[3] who, with Nicol as his earlier colleague, showed that an ancient gneiss is unconformably overlain with a thick mass of dull red sandstones above which lie (also unconformably, as was eventually discovered) quartzites and limestones containing fossils which he referred to the Lower Silurian system. He regarded the red sandstones as probably Cambrian, and after proposing the terms Fundamental and Lewisian for this underlying gneiss, he finally adopted instead of them the term Laurentian, believing that the rocks so designated by him in this country were equivalents of those which had been studied and described by his friend Logan in Canada.[4] More recently the officers of the Geological Survey have discovered the *Olenellus*-zone in strata intermediate between the quartzites and the limestones.[1] These formations are thus shown to be of Cambrian age. The base of the Cambrian series in the north-west of Scotland lies at the bottom of the quartzite which reposes with a strong unconformability, sometimes on the red sandstones, sometimes on the gneiss. Hence these last two distinct groups of rock are now definitely proved to be pre-Cambrian. As they differ so strongly from each other their respective limits can be easily followed, and as they extend over a united area of hundreds of square miles in the north-west of Scotland they afford abundant opportunities for the most detailed examination. The rocks of this region may be arranged in descending order as in the following table:—

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[1] 'A Description of the Western Islands of Scotland,' 1819.

[2] 'Geognostical Account of the County of Sutherland,' *Highland Soc. Trans.* viii. (1841) p. 73.

[3] *Brit. Assoc.* 1885, Sect. p. 85; 1857, Sect. p. 82; 1858, Sect. p. 94; *Quart. Journ. Geol. Soc.* xiv. (1858) p. 501; xv. (1859) p. 353; xvi. (1860) p. 215; xvii. (1861) p. 171. Nicol, *Quart. Journ. Geol. Soc.* xiii. (1857) p. 17; xvii. (1861) p. 85; *Brit. Assoc.* 1858, Sect. p. 96; 1859, Sect. p. 119.

[4] In the elucidation of the true relations of the rocks to each other in the N.W. of Scotland later geologists have taken part, more especially Dr. Hicks, Prof. Bonney, Mr. Hudleston, Dr. Callaway, and above all, Professor Lapworth and the officers of the Geological Survey. The literature of the subject, up to 1888, will be found condensed in the Report by the Geological Survey, in *Quart. Journ. Geol. Soc.* vol. xliv. (1888) p. 378. The more important announcements since that date will be referred to in the sequel.

Cambrian.		Limestones of Durness with numerous fossils indicating Cambrian and possibly lowest Silurian horizons (p. 730).
		Serpulite grit and "Fucoid beds," with *Salterella* and *Olenellus* = Olenellus zone.
		Quartzites with abundant worm-burrows.
		[Unconformability.]
Pre-Cambrian.	Torridonian.	Dull red sandstones, shales and conglomerates attaining a thickness of at least 8000 or 10,000 feet, the upper limit being lost by denudation and unconformability.
		[Strong unconformability.]
	Lewisian.	Coarse gneisses and schists derived from a complex aggregate of eruptive rocks of different ages by mechanical deformation. In one area there appears to be a group of still more ancient and sedimentary rocks through which the gneisses have been intruded.

LEWISIAN.—The oldest gneisses of Scotland form the Isle of Lewis with the rest of the Outer Hebrides, and extend in an interrupted band on the mainland from Cape Wrath at least as far as Loch Duich. For this important and well-defined group of rocks the name Lewisian, formerly proposed by Murchison, seems most appropriate. As originally studied, it was thought to be a comparatively simple formation. Its foliation-planes, like those of other similar rocks, were supposed to mark layers of deposit, and to show that the rocks were metamorphosed sediments. It was believed to have been thrown into sharp anticlinal and synclinal folds, of which the axes ran in a general north-westerly direction. The detailed mapping of the region by the Geological Survey, however, has shown that the apparent bedding is wholly deceptive, and that the seeming simplicity gives place to an extraordinarily complex structure. Instead of being altered sediments, the rocks have been ascertained to consist essentially of eruptive masses, varying from an extremely basic to a markedly acid type, and belonging to successive periods of extrusion.[2]

As a whole the gneiss is considerably more basic than the typical rocks to which this term was originally given. It commonly consists of plagioclase felspar with pyroxene, hornblende, and magnetite, sometimes with blue opalescent quartz, and sometimes with black mica. These predominant minerals are sometimes distributed quite without structure, so that the rock appears as a syenite, diorite, gabbro, peridotite, picrite, pyroxene-granulite, or other massive amorphous member of the eruptive rocks. From these structureless areas, which probably represent most nearly the original condition of the materials, gradations can be traced into well foliated masses, and into coarsely banded gneisses, where the minerals have segregated into lenticular bands and elliptical or irregular concretions. Though it may often be difficult in practice to distinguish types of structure among these rocks, two such types may in many instances be recognised. In the first place, there is the banded or segregated structure, in which the predominant minerals have separated out from each other, and have crystallized more or less apart, often in coarse aggregations, forming in this way distinct bands or folia which, since they are often crossed by the planes of foliation, are evidently older than the development of these planes. The bands consist sometimes of pyroxene or hornblende, with little or no plagioclase, or of plagioclase with small quantities of the ferro-magnesian minerals and quartz, or mainly of plagioclase and quartz, or largely of magnetite. This structure probably belongs to the time when the rock existed as an erupted material. It resembles in many respects the segregation layers to be found in some sills or bosses of eruptive materials (gabbros, dolerites, &c.) which have cooled and crystallized slowly at some considerable depth from the surface. In the second place, there is abundant evidence of mechanical deformation of the gneiss, especially along planes in certain directions The rock has been powerfully ruptured and crushed in these lines, and has thereby acquired a granulitized and distinctly foliated structure.

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[1] *Brit. Assoc.* 1891, Sect. p. 633. Peach and Horne, *Quart. Journ. Geol. Soc.* xlviii. (1892) p. 227.

[2] For details regarding the gneiss of N.W. Scotland, and the remarkable geological structure of that region see the report of the Geological Survey, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 378, where the work of Messrs. Peach, Horne, Gunn, Clough, Hinxman, and Cadell is summarised.

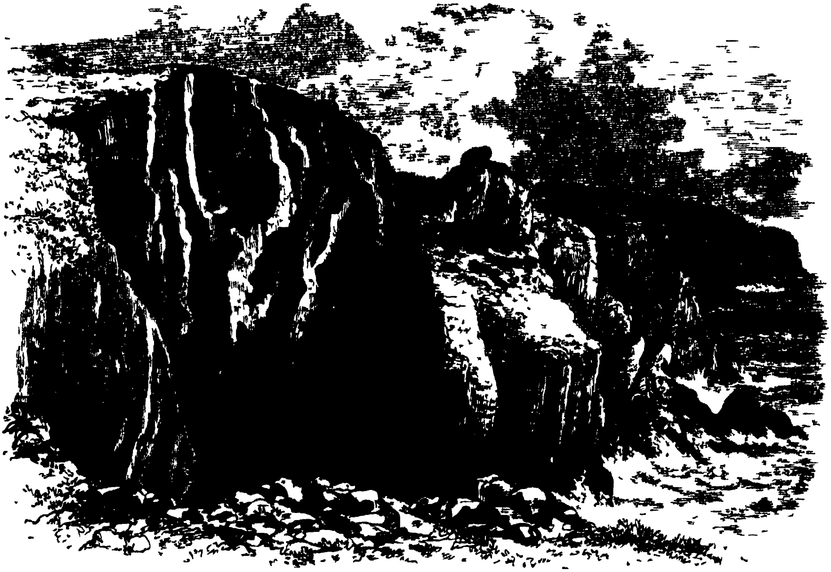
Fig 326 —Veins of pegmatite in gneiss, south of Cape Wrath.

Both in the massive and in the coarsely-banded gneisses abundant pegmatite veins occur, varying in width from a few inches to several yards, and consisting mainly of felspar and quartz. These grey veins, sometimes so numerous as to constitute a large proportion of the whole rock, occasionally enclose patches of the dark more basic rock around them, but have no determinate grouping (Fig. 326).

The pegmatites are found to have played an important part in the ultimate constitution of the gneiss. Where still quite traceable, but where they have come within the influence of mechanical deformation, they appear as rudely parallel and puckered bands (Fig. 327). But as we pass into the more thoroughly foliated portions of the gneiss, the original character of the pegmatites is found to be more and more affected, until it becomes no longer recognisable in the acquired schistose structure. The dark basic portions of the original mass pass into rudely foliated basic gneisses, and the grey pegmatites shade into the more quartzose bands associated with them. Thus the derivation of the gneisses from amorphous igneous rocks may be regarded as established beyond dispute.

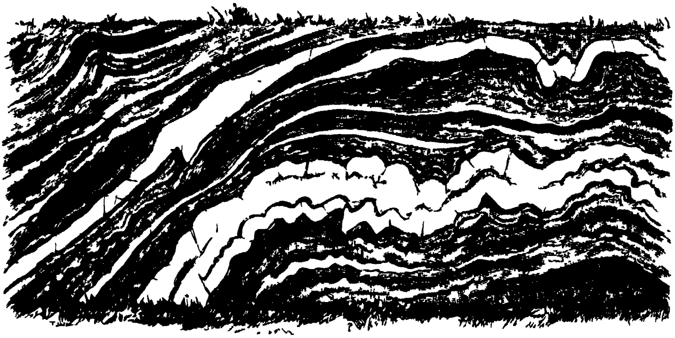

Fig. 327.—Gneiss with deformed pegmatites—Cape Wrath.

As illustrative of the conclusion that while there seems good reason to believe that the segregated or coarsely-banded structure indicates a separation and crystallization of materials out of a still unconsolidated igneous magma, the predominant foliation structures which traverse these bands were produced by powerful mechanical movements, such a section as that represented in Fig. 328 may be cited. The mineral bands have there been violently plicated, and have been cut through by a succession of thrust-planes (*t t*), by which they have been pushed forward and piled over each other. The foliation thus superinduced follows the direction of movement, and crosses indiscriminately the boundaries of the different aggregates of original materials. Viewed from a little distance the darker and lighter crumpled layers form a striking feature on many coast cliffs, but they are seen to be abruptly truncated above and below by thrust-planes parallel to which the gneiss has sometimes been crushed and rolled out into flaggy sheets (Fig. 329). These ancient structures are similar to those so abundantly developed in the younger or eastern gneisses already (p. 625) referred to. They seem to make it certain that after the consolidation of the complex assemblage of igneous rocks and the production of their pegmatites, a series

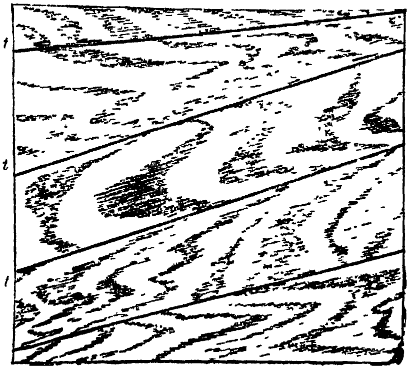

Fig 328.[1]— Section of Lewisian gneiss, embracing a vertical surface of several hundred square yards.

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[1] Figs. 328, 331, 334 are taken by permission of the Council of the Geological Society from the Report of the Geological Survey published in the Quarterly Journal of the Society for August 1888.

of powerful mechanical movements crumpled, crushed, and sheared the whole mass, and produced in it a distinct foliation. Portions of one kind of material, such as dark hornblende, have been separated from the rest, and have been involved as distinct lumps in another variety such as grey quartzose gneiss.

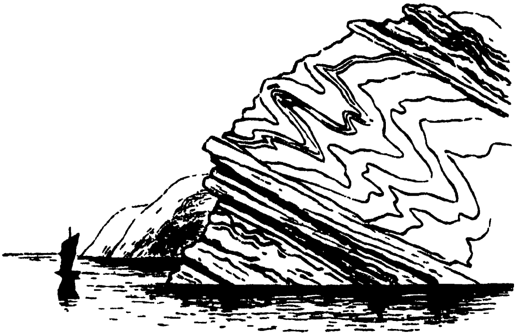

Fig. 829.—Plicated banded gneiss between masses that have been sheared parallel to the thrust-planes, north side of Loch Torridon.

The detailed investigations of the Geological Survey have further shown that, after the first foliation had been superinduced, a new series of igneous protrusions invaded the gneisses, chiefly in the form of dykes. The earliest and most conspicuous of these are extraordinarily abundant basalt-rocks, running as long parallel bands in a general W.N.W. and E.S.E. direction. The latest are dykes of granite or syenite, while probably of intermediate date, are certain highly basic dykes, among which peridotite and picrite are characteristic. The evidence as to the relative dates of these igneous intrusions being tolerably clear, we have here proofs of a long interval of subterranean activity, during which the magma that was first injected into the gneiss in such basic form as basalt parted progressively with its more basic constituents until it became in the end quite acid. It is interesting to find, even among the most ancient rocks of Britain, a sequence of eruptive materials, like that which appears so markedly among the Palæozoic and Tertiary volcanic phenomena (p. 262).

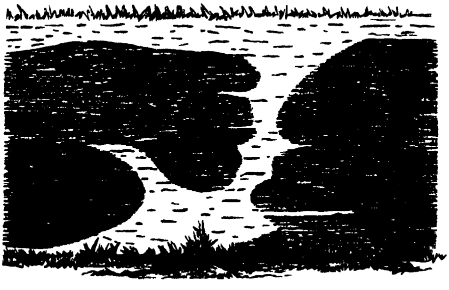

Fig. 830.—Foliation induced in a granite vein in gneiss, Loch Laxford.

After the injection of these various eruptive materials, the whole region of the north-west of Scotland was once more subjected to powerful dynamic movements, whereby all the rocks were profoundly affected. The results of these operations are found partly in vertical lines or bands of rupture or crushing, along which, sometimes for a breadth of 500 feet or more, the rocks have been crushed or sheared, partly in thrust-planes which are often nearly flat. In some instances the intrusive dykes remain quite distinct, but have acquired a more or less distinct foliated structure, the planes of foliation being parallel to those which traverse the surrounding gneiss (Fig. 330). But the alterations produced by these enormous terrestrial stresses are most strikingly displayed by some of the more basic dykes.

Along the central portions of one of the basalt or dolerite dykes, the massive rock may be observed to have been broken into oblong lenticles round which the more crushed material passes into hornblende-schist, while the outer portions of the dyke likewise become entirely schistose (Fig. 332). So great has been the metamorphism that the augite for the most part has been changed into hornblende. The felspars have assumed an opaque granular condition, and the rock becomes a diorite. The peridotite and picrite dykes have been converted into soft talcose schists, the veins and belts of granite into granitoid gneiss. Such, too, has been the compression that in some cases dykes of 50 or 60 yards in breadth are reduced, where one of these crush-lines crosses them obliquely, to a thickness of no more than four feet, while the horizontal displacement sometimes amounts to a quarter of a mile (Fig. 331). Besides foliation produced parallel to the vertical or highly inclined lines of movement, a similar structure has been superinduced in the gneiss parallel to the gently inclined thrust-planes.

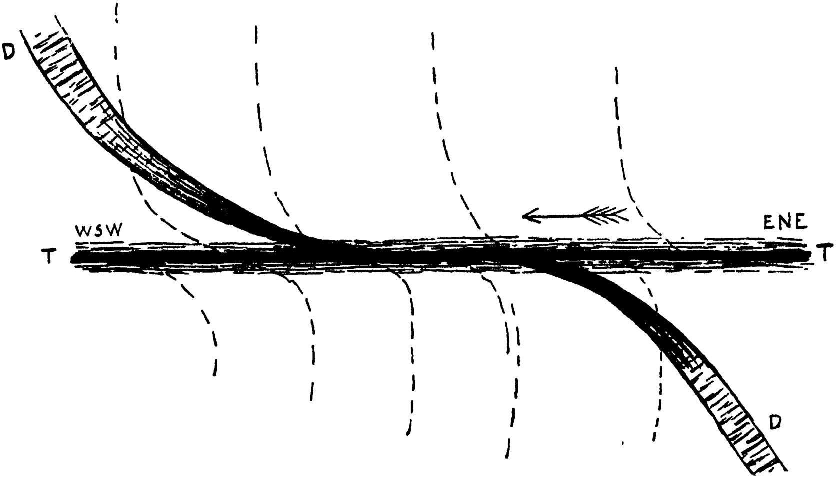

Fig. 331.—Ground-plan showing deflection and disruption of dykes in the Lewisian gneiss of N.W. Scotland.

TT, Thrust-plane, DD, Dyke, deflected about ¼ mile and much compressed. The dotted lines show the strike of the gneiss and its displacement by the thrust-plane; the fine parallel lines in the dyke and in the gneiss mark the direction of the newer schistosity developed by the thrust-movement, which was in the direction of the arrow.

The influence of these movements, not only on the amorphous dykes and veins, but on the general body of the already foliated gneiss itself, has been profound. Where the change has been most complete a new foliation has completely obliterated the original structure. From this extreme every gradation may be traced back to the first schistose structure, and thence into the original amorphous condition. In many cases this new foliation has been produced nearly or quite along the planes of the old structure. But everywhere examples may be observed where (as in Fig. 333) the alternate bands of lighter and darker material are traversed obliquely by the newer structure, which may be perfect in the dark more basic bands and hardly developed in the grey more quartzose parts.

It is obvious that the various terrestrial movements indicated by the complex composition and structure of the Lewisian gneiss must represent a protracted period of geological time. But there is demonstrative evidence that the whole of them had been completed, and that the rocks in which they took place at a great depth had been exposed at the surface by vast denudation before the next member of the pre-Cambrian series was formed. The Torridon sandstone lies with the most complete unconformability on the old gneiss, covering alike its dykes, crush-lines and thrust-planes, by not one of which is it in the least degree affected. It is of course impossible to form any adequate conception of the length of time denoted by this unconformability. But the more the geologist tries to realise what the denudation of the old gneiss involves, the more impressed will he be with the vastness of the period which it denotes.

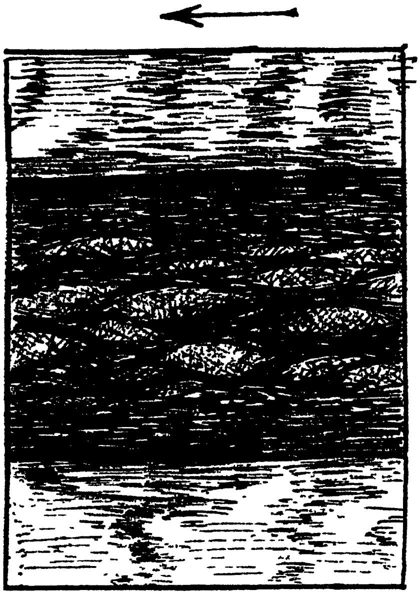

Fig. 332. Diagram of dolerite dyke cutting Lewisian gneiss, representing an area of about 600 square yards. The dark portion represents the dyke with its "eyes" or lenticles surrounded by and passing marginally into hornblende-schist. The grey band on either side of the dyke is the surrounding gneiss which has been affected by a secondary foliation parallel to that of the dyke. The arrow shows the direction of movement.

Over nearly the whole of the Lewisian gneiss, so far as it has been studied on the mainland, no trace has been found of any rocks save what probably had an eruptive origin. In one district, however, which includes the picturesque valley of Loch Maree, a remarkable group of rocks occurs which, though their exact relations are not without some doubt, appear to indicate a sedimentary series through which the Lewisian gneiss has been erupted. These rocks consist chiefly of fine mica-schist, quartz-schist, graphite-schist and limestone. The graphitic material occurs in bands an inch or more thick in the mica-schist. The limestones are persistent beds,

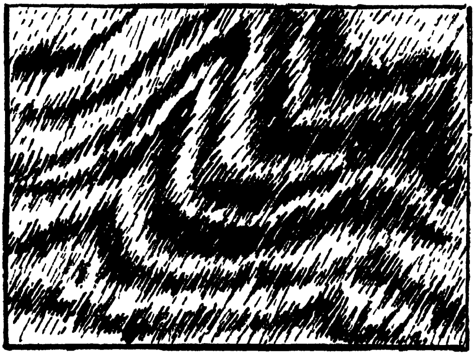

Fig. 333.—Diagram showing later oblique foliation crossing the original banding of the Lewisian gneiss (about nat. size).

having generally a saccharoid texture, and sometimes full of the usual minerals found in a marble in a zone of contact-metamorphism. The line of junction of this group of rocks with the gneiss is well defined, but does not distinctly show any intrusion of the latter, appearing rather to have resulted from movement with concomitant crushing. If these strata, so similar in many respects to the undoubted altered sedimentary masses of the central Highlands, are eventually proved to be truly of sedimentary origin they will possess a high interest as the oldest geological formation yet known in Britain or in Europe.[1]

In some portions of the north-west of Scotland, especially in the north of Sutherland, the surface of the gneiss has been reduced, after prolonged denudation, to a kind of level platform on which the Torridon Sandstone has been deposited. But further south that surface presents a singularly uneven character rising into heights 3000 feet above the sea and sinking into hollows that descend below sea-level. In the rugged mountainous ground between Lochs Maree and Broom this primeval land-surface is impressively displayed, for the thick mantle of red sandstone under which it was buried and preserved has been irregularly stripped off, and the details of the pre-Torridonian topography can easily be traced.

TORRIDONIAN.—From Cape Wrath, at the extreme north-west end of Scotland, southwards for more than 100 miles, there stretches a broken belt of singular conical or pyramidal hills, rising sometimes to more than 3000 feet above the sea, and presenting alike in their form and colouring a striking contrast to the rest of the scenery of that region. They are built up of nearly horizontal or gently inclined strata of reddish-brown or chocolate-coloured sandstones and conglomerates, which lie with a violent unconformability on the gneisses above described, and are in turn covered unconformably by the quartzites which form the base of the Cambrian system. Where most fully developed, in the south-west of Ross-shire, these strata are between 8000 and 10,000 feet thick. They have doubtless been derived from the waste of the Lewisian rocks, though pebbles occur in them which have not been identified with any material in the older formation. Some of the conglomerates are so coarse as to deserve the name of boulder-beds. Sometimes, indeed, where the component blocks are large and angular, as at Gairloch, they remind the observer of the stones in a moraine or in boulder-clay.[2] Some of the sandstones are in large measure composed of pink felspar derived from such rocks as the pegmatites of the surrounding gneiss. An occasional thin band may be found among them consisting largely of grains of magnetite and zircon, whence we learn at what an ancient epoch in geological history heavy and durable grains were separated out from the more ordinary sediment (see p. 129). In the highest visible portion of these sandstones a group of shales occurs, and another more important group with thin bands of impure limestone forms a prominent feature near the base of the series in the west of Ross-shire. These strata may yet yield recognisable fossils, but hitherto except some tracks and other obscure markings no trace of organic forms has been met with in them.

Messrs. Peach and Horne have detected near Loch Inver a band of fine volcanic tuff among the red sandstones, showing the contemporaneous activity of some volcanic vent in that district. Small vesicular pebbles of porphyrite found among the contents of the conglomerates may perhaps indicate the outflow of lavas.

The strata now under consideration are abundantly displayed among the mountains that surround Loch Torridon, one of the most picturesque inlets in the north-west of Scotland. Hence they were called by Nicol the Torridon Sandstone. They were originally supposed to be Old Red Sandstone, and to represent the lower sandstones and conglomerates of that system in the East of Sutherland and Ross. After the discovery of what were believed to be Lower Silurian fossils in the Durness limestones, Murchison assigned these sandstones to the Cambrian system. But the recent detection of the

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[1] See *Brit. Assoc.* 1891, Sect. p. 634.

[2] Nature xxii. (1880) p. 402.

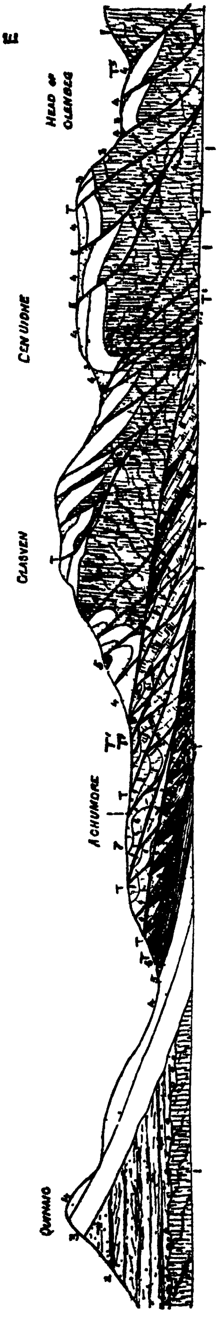

Fig 334.—Section from Quinaig (2653 feet) eastwards through Glasven (2541 feet), Sutherland (*Quart. Journ. Geol. Soc.* 1888, p. 418). Cambrian.—7. Limestone; 6. Serpulite grit; 5. Fucoid beds; 4, 3. Upper and lower Quartzite. Pre-Cambrian.—2. Torridon Sandstones; 1. Lewisian gneiss. T. Thrust-planes; T'. Maximum Do.

Olenellus-zone among the strata which unconformably overlie them proves that they must be of still older date. They are now classed as Torridonian in the pre-Cambrian formations or systems of Britain.

The interval between the deposition of the highest visible portion of the Torridonian series and the base of the Cambrian formations must have been of prolonged duration. For not only had the red sandstones been upraised, but they had been profoundly trenched by denudation. So vast and unequal was the erosion that while at one place the lower quartzites are seen reposing on 3000 or 4000 feet of Torridon sandstone, at another only a few miles distant they rest directly on the Lewisian gneiss, the intervening massive group of strata having been entirely bared away.[1]

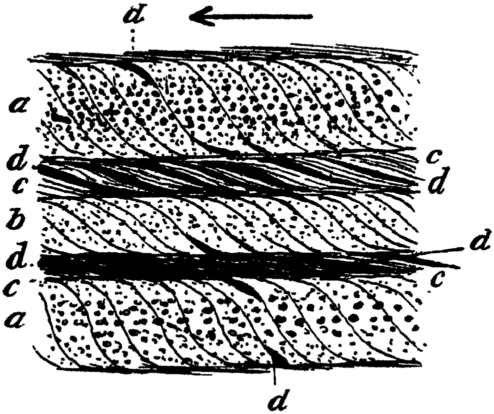

Fig 335.—Diagram of altered Torridon sandstone, Coinne-mheall, Assynt.

a, Coarse grit or arkose; *b*, finer do.; *c*, shale; *d*, pegmatitic material developed as a consequence of the crushing of the rocks by movement in the direction of the arrow.

But besides the solid areas of pre-Cambrian rocks in the north-west of Scotland there are extensive tracts where these rocks do not remain in their original positions, but have been pushed into their present places by great subterranean disturbances, and have actually been shoved over strata of recognisably Cambrian age. In the account already given (pp. 624-27) of the structure of that region it was shown that by these earth-movements slice after slice of the Lewisian gneiss and of the Torridon sandstone has been shorn from the mass of these formations below ground, has been piled one on the other, and has been driven westward over the Cambrian strata which originally lay above them; that the rocks, subjected to such enormous pressure, dislocation and deformation, have undergone serious metamorphism; and that finally by a gigantic rupture and thrust a thick series of gneissose flagstones ("Moine schists") have been brought forward. By way of further explanation of this extraordinary structure the annexed sections are given (Figs. 334, 335). It will be seen what an enormous body of gneiss has here been displaced and pushed over the Cambrian strata, which in turn have been cut into slices and piled up above and against each other. Among the alterations of the Torridon sandstones one of the most interesting is the production of pegmatitic veins in them, like those which traverse eruptive rocks. These strata have been crushed and stretched in such a manner that ruptures, often lenticular in form, have been produced in them. In the cavities thus caused there has been a deposition of quartz and of quartz and pink felspar (Fig. 335).

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[1] This structure is shown both in Figs. 311 and 334.

With regard to the rocks which have been thus displaced and metamorphosed, it is extremely difficult to form a satisfactory opinion as to the probable source and original condition of many of them. Portions of the Lewisian gneiss can be recognised, and in the west of Inverness-shire this rock probably constitutes a large proportion of the reconstructed schistose series which has been thrust westward over the Cambrian limestones and quartzites. The Torridon sandstones also can occasionally be identified, and they may constitute a not inconsiderable proportion of the "upper gneiss" of Western Ross-shire. Possibly other sedimentary material, such for instance as any which succeeded the Durness limestones, may have been involved in the gigantic crushing movements that produced the younger or eastern schists. As the detailed work of the Geological Survey advances the sources from which these schists have been derived may be more fully known. But the great fact has been abundantly established that the movements which pushed the rocks into their present positions and imparted to them their existing foliation took place after Cambrian time, and before the period of the Old Red Sandstone. We have thus a notable example of extensive regional metamorphism during the Palæozoic ages.

In the central, southern, and eastern Highlands of Scotland, that is, throughout the hilly ground east and south of the line of the Great Glen, an important series of metamorphic rocks is largely developed, the true stratigraphical position of which is not yet certainly known. They consist in large proportion of altered sedimentary strata, now found in the form of mica-schist, graphite-schist, andalusite-schist, phyllite, schistose-grit, greywacke and conglomerate, quartzite, limestone, and other rocks, together with epidiorites, chloritic schists, hornblende-schists, and other allied varieties which probably mark sills, lava-sheets or beds of tuff, intercalated among the sediments. The total thickness of this assemblage of rocks must amount to many thousand feet. Some of its members are so persistent as to form recognisable horizons, and to afford a basis for some approximation to a stratigraphical arrangement of the whole. In Perthshire, for example, the following groups in descending order have been mapped by the Geological Survey:—

Dark schist and limestone (Blair Athol).
Quartzite (Ben-y-Gloe).
Graphite-schist.
Calcareous sericite-schist, and sericite-schist with bands of quartzite. On this horizon occurs a great mass of epidiorite and hornblende-schist.
Garnetiferous mica-schist and schistose pebbly grits.
Limestones (Loch Tay). Hornblende-schists occur above and below this horizon.
Garnetiferous mica-schists, schistose grits, with pebbly bands and thick bands of "green schists." Hornblendic sills begin to appear in this group.
Massive grits with schists and conglomerate containing pebbles sometimes as large as a pigeon's egg. (Ben Ledi, Loch Achray, &c.)
Zone of slates (Aberfoyle).
Pebbly greywacke and grit with black shales and limestone below (Pass of Leny).

The Loch Tay Limestone has now been traced completely across the country from the Moray Firth through the Grampian Mountains to the west of Argyllshire, and some of the other zones have been followed for many miles. The metamorphosed condition of the rocks varies considerably, not only according to their composition, but even along the line of strike of the same group. On the whole the alteration appears to be most intense in the Central Highlands, and to become less as the rocks recede from that area towards the north-east and south-west. One of the most singular and instructive instances of this variation is that which has recently been mapped by Mr. J. B. Hill of the Geological Survey in the district of Loch Awe. A series of grits, phyllites, and limestones, resembling ordinary Palæozoic sediments, has there been followed by him north-eastwards, and has been found to pass along the strike into the thoroughly crystalline schists of the Central Highlands. Mr. Barrow of the Geological Survey has found the metamorphism in Forfarshire to be probably connected with the protrusion of large bodies of granite which often passes into a variety of gneiss. After the great terrestrial movements by which the rocks were folded and metamorphosed, large bodies of eruptive material, notably granite, invaded the schists and produced extensive metamorphism, as already stated (p. 627). The change is most intense near the granite, where sillimanite embedded in quartz is a conspicuous mineral in the schists. A little farther away comes a band in which kyanite is often abundant, while at a still greater distance the predominant mineral is staurolite. These three successive zones of contact-metamorphism can be found passing through the same band of aluminous schistose material as it recedes from the eruptive rock.

At present no definite opinion can be expressed as to the stratigraphical position of this important group of metamorphic rocks, which forms the greater part of the Highlands of Scotland. On the one hand, it is conceivable that they may all be pre-Torridonian. They may be of the age of the Loch Maree limestones and mica-schists above referred to (p. 704); or they may represent some part of the vast interval denoted by the unconformability between the Lewisian gneiss and the Torridon sandstone; or again they may possibly include that sandstone and the sedimentary deposits which conformably succeeded it, and which are absent in the North-west Highlands. On the other hand, they may include, as Murchison believed, representatives of the quartzites and limestones of Durness, and even of later sedimentary formations which may have succeeded these strata, but of which, as we now know, no trace remains in the North-west Highlands.[1] It is thus still an open question whether the metamorphic rocks which constitute the main part of the Scottish Highlands are of pre-Cambrian or of Cambrian, or even possibly in part of Silurian age. They are not confined to Scotland, but spread over many hundreds of square miles in the north and west of Ireland. As it is convenient to avoid periphrasis by having a short name to designate so important a series of rocks, I have proposed to call them provisionally *Dalradian*, after the old Celtic kingdom of Dalriada, which, originally fixed in the north of Ireland, subsequently extended into the south-west of Scotland, and finally gave the name of Scotland to the kingdom which bears that appellation.[2] I have little doubt, however, that before long it will be possible to make out satisfactorily the structure of the central and southern Highlands, and to show the presence and areas of Lewisian, Torridonian, Cambrian, and even Lower Silurian rocks in that region.

In the north and west of Ireland crystalline schists and eruptive rocks cover a large area; but as the rocks which unconformably overlie them are not of higher antiquity than the Carboniferous and Old Red Sandstone there is no absolute proof in that country of their pre-Cambrian age. There cannot, however, be any doubt that it is the Dalradian series of limestones, quartzites, phyllites, mica-schists, epidiorites, granites, and other crystalline rocks, which crosses from Scotland and spreads across the northern and western counties of Ireland. The Irish development of these rocks is similar to their grouping in Scotland, some of the bands of quartzite, conglomerate, limestone, phyllite, and mica-schist being probably continuations of similar bands on the Scottish mainland

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[1] Along the Highland border the remarkable band of cherts and igneous rocks referred to on p. 627 may not improbably show the presence there of the radiolarian cherts and volcanic zone at the base of the Lower Silurian series of the Southern Uplands.

[2] Presidential Address, *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 75.

and in the islands of Argyllshire.[1] But there are also scattered areas of coarsely-banded gneisses which present the closest resemblance to parts of the Lewisian gneiss of Scotland. The best areas for the study of these rocks lie near Pettigoe and Ballyshannon (Donegal), from Erris Head to Blacksod Point (Mayo), in the Slieve Gamph or Ox Mountains stretching from Castlebar beyond Sligo to Manor Hamilton, and in the western part of the County of Galway. The relations of the Dalradian series to the gneisses and granitoid rocks have not yet been accurately determined. But there is reason to believe that the former rests with a violent unconformability upon the latter. Near Castlebar, Mr. A. M'Henry, of the Geological Survey, has recently found at the base of the Dalradian schists a coarse conglomerate made up largely of fragments of the gneisses and granites on which it rests.

In England and Wales many isolated areas have been described as pre-Cambrian on evidence which, as already stated, cannot be considered satisfactory.[2] The areas where in my opinion the most satisfactory evidence of pre-Cambrian rocks can be produced are Anglesey, the Caer Caradoc and Longmynd area and the Malvern Hills. Of these areas by much the most important is the first named. In Anglesey the *Olenellus*-zone has not been discovered, but the fossils found indicate Tremadoc and possibly even Menevian horizons in the Lower Cambrian series.[3] The basement strata are conglomerates, and they evidently lie with a marked unconformability on certain crystalline schistose rocks. It was the belief of Sir A. C. Ramsay that the latter were metamorphosed portions of the Cambrian system, and they were so represented on the Geological Survey maps. But a re-examination of the ground leads to the conclusion that they had acquired their present crystalline characters before the Cambrian strata were laid down upon them; and as these strata belong to a low part, if not the base, of the Cambrian system, it becomes manifest that the schists must be of pre-Cambrian age.[4]

Two groups of schistose rocks, which differ considerably in petrographical characters, have been detected in Anglesey. One of these, consisting mainly of coarse gneisses, abounding in hornblende, garnets, and brown mica, and with coarse pegmatite veins, presents a close resemblance to portions of the Lewisian series of N.W. Scotland. The other group occupies a much larger area, and is composed of flaggy chloritic schists, green and purple phyllites or slates, quartzite, grit, and other more or less recognisably clastic rocks. The resemblance of these masses to the Dalradian series of Scotland and Ireland is striking. The quartzites of Holyhead contain annelide burrows. The exact stratigraphical relations of the two crystalline groups to each other have not yet been satisfactorily determined. There was probably an original unconformability between them, like that referred to as occurring in the west of Mayo.[5] It may be regarded as a well-established fact in British Geology that early in the Cambrian period there existed at least one tract of old crystalline rocks above water in the north-west of Wales.

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[1] The fullest account of these Irish metamorphic rocks will be found in the Memoirs of the Geological Survey of Ireland; see especially those on Sheets 1, 2, 5, 6, and 11 (Inishowen, Co. Donegal); 3, 4, 5, 9, 10, 11, 15, and 16 (N.W. and Central Donegal); 22, 23, 30, and 31 (S.W. Donegal); 31 and 32 (S.E. Donegal). See also Harkness, *Quart. Journ. Geol. Soc.* xvii. (1861) p. 256; Callaway, *op. cit.* xli. (1885) p. 221.

[2] There is now a voluminous literature on this subject; only some of the more important papers will be here cited.

[3] Prof. Hughes, *Quart. Journ. Geol. Soc.* xxxvi. (1880) p. 237; xxxviii. (1882) p. 16.

[4] Prof. Hughes, *op. cit.* xxxiv. (1878) p. 137, xxxv. (1879) p. 682; *Brit. Assoc.* 1881, Sects. p. 643; *Proc. Camb. Phil. Soc.* iii. pp. 67, 69, 341. Prof. Bonney, *Quart. Journ. Geol. Soc.* xxxv. (1879) pp. 300, 321; *Geol. Mag.* 1880, p. 125. Dr. Hicks, *Quart. Journ. Geol. Soc.* xxxiv. (1878) p. 147; xxxv. (1879) p. 295; *Geol. Mag.* 1879, pp. 433, 528. Dr. Callaway, *Quart. Journ. Geol. Soc.* xxxvii. (1881) p. 210, xl. (1884) p. 567. Prof. J. F. Blake, *op. cit.* xliv. (1888) p. 463; *Brit. Assoc.* 1888 (Report on Microscopic Structure of Anglesey Rocks).

[5] *Quart. Journ. Geol. Soc.* xlvii. (1891) Address, p. 82. Mr. Blake has proposed the name of "Monian System" for the pre-Cambrian rocks of Anglesey. In the Address just quoted I have given reasons for my inability to adopt this term.

On the borders of Shropshire and Wales a ridge of ancient rocks rises up from under Silurian strata which lie upon it unconformably. Part of this ridge consists of eruptive material which was formerly believed to be of later date than the sedimentary rocks immediately around. But the main portion of the high ground is formed of a thick series of evidently very old grits, slates, and other clastic deposits, which, though hardly any trace of organic remains had been found in them, were assigned to the Cambrian system. More recent researches, however, have shown the presence of the *Olenellus*-zone in this district at the base of a group of strata which are thus definitely proved to be lower Cambrian.[1] From this important horizon it is possible to work backward and to show that underlying these basement parts of the Cambrian system a remarkable group of igneous rocks comes to the surface. The investigations of Mr. Allport and Dr. Callaway have shown that these rocks include both lavas and fragmental ejections varying from coarse breccias to fine tuffs. The lavas are generally felsitic in character, showing true rhyolitic structures, but there occur also bands of diabase which may possibly be sills. There is thus clear evidence of a copious ejection of volcanic materials in this part of England before the oldest Cambrian formations were laid down.[2]

Though the evidence is not perhaps conclusive, it seems to point to an unconformability between the base of the Cambrian system and this volcanic group, which would thus probably be of pre-Cambrian date. The relation of the volcanic masses to the great thickness of ancient sedimentary strata constituting the Longmynd ridge has not yet been satisfactorily determined, though there are indications that the volcanic group lies at the bottom. Dr. Callaway has proposed the name *Uriconian* for that group, and *Longmyndian* for the thick series of sedimentary strata lying to the westward. Those names may be provisionally accepted. The Longmyndian rocks have generally been assigned to the Cambrian system, and they may possibly still be shown to belong to that part of the geological record. The Uriconian volcanic group, however, is probably pre-Cambrian.

In other parts of England and Wales isolated areas have been described as containing pre-Cambrian rocks. Of these the district of St. David's in Pembrokeshire has attracted the largest share of attention, chiefly through the labours of Dr. Henry Hicks, who in that small area has endeavoured to establish the existence of three distinct pre-Cambrian formations. At the base, under the name of "Dimetian," he places what he considers to be granitoid and gneissic rocks with bands of impure limestone or dolomite, schists and dolerite. Above these he distinguishes as "Arvonian" a group composed essentially of rhyolitic felstones, breccias, and tuffs, marking volcanic eruptions of an acid type, while at the top he describes, by the designation "Pebidian," a series of tuffs and slates.[3] After a careful study of the ground I came to the conclusion that there is no trace of pre-Cambrian rocks at St. David's. I regard the so-called "Dimetian" as a granite which has invaded the Cambrian rocks; the "Arvonian" includes the quartz-porphyries, which appear as apophyses of the granite; while the "Pebidian" is an interesting group of basic lavas and tuffs which form here the lowest visible part of the Cambrian system (referred to at pp. 727, 728). A similar group of breccias and tuffs underlies the Cambrian slates of Llanberis, and has likewise been claimed as pre-Cambrian, but it can be shown to pass up continuously into the Cambrian strata. In the Malvern Hills a core of gneissose and schistose rocks is doubtless of pre-Cambrian age, fragments derived from it being found at the base of the overlying unconformable Cambrian strata.[1] From the plains of Leicestershire rises an insular area of rocky hills (Charnwood Forest) composed of slates, tuffs, and various crystalline rocks, which by the Geological Survey have been coloured as altered Cambrian. Messrs. Bonney and Hill, who have fully described these rocks, regard them as of pre-Cambrian date, and show to what a large extent they are composed of volcanic agglomerates and tuffs.[2] No conclusive evidence, however, has been adduced that these rocks are pre-Cambrian. The slates resemble some of the Cambrian slates of Wales, and the volcanic rocks may be compared with those which in that principality lie at the base of the Cambrian system. Another protuberance of ancient rocks rises in Central England from beneath the coal-field of eastern Warwickshire. In this instance a definite age can be assigned to one portion of the rocks, for they contain Upper Cambrian fossils.[3] Beneath these strata, and apparently in conformable sequence with them, lies a well-marked volcanic group. The occurrence of this group in the position which it occupies affords support to the belief that the volcanic rocks elsewhere conjectured to be pre-Cambrian really belong to the Cambrian system. At the Lizard Point in Cornwall a series of eruptive and schistose rocks occurs, the true relations of which have not yet been fixed. They may be pre-Cambrian. They include coarse gneisses which rise as islets near the coast.

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[1] Lapworth, *Geol. Mag.* 1888, p. 484.

[2] S. Allport, *Quart. Journ. Geol. Soc.* xxxiii. (1877) p. 449. C. Callaway, *op. cit.* xxxiii. p. 652, xxxiv. (1878) p. 754, xxxv. (1879) p. 643, xxxviii. (1882) p. 119, xlii. 1886) p. 481, xlvii. (1891) p. 109; *Geol. Mag.* 1881, p. 348; 1884, p. 362; 1885, p. 260. J. F. Blake, *Quart. Journ. Geol. Soc.* xlvi. (1890) p. 386.

[3] *Quart. Journ. Geol. Soc.* xxxi. (1875) p. 167, xxxiii. (1877) p. 229, xxxiv. (1878) p. 153, xxxv. (1879) p. 285, xl. (1884) p. 507. My account of the so-called pre-Cambrian rocks of St. David's will be found in *Quart. Journ. Geol. Soc.* xxxix. (1883) p. 261. Prof. Lloyd Morgan has since confirmed my main conclusions, *op. cit.* xlvi. (1890) p. 241. Compare also J. F. Blake *op. cit.* xl. (1884) p. 294.

On the continent of Europe numerous isolated areas of schists and other ancient rocks have been assigned to a pre-Cambrian or Archæan series. In the older descriptions of these tracts an order of succession was often given, the foliation being assumed to represent consecutive layers of deposition. But we now know that, in the great majority of cases, the foliation is entirely independent of original structure, so that the former attempts to establish a stratigraphical order among the gneisses and schists, and to compare that order in different countries, cannot be accepted. All that can be attempted here is to give a summary of the general characters of the most ancient rocks of each region referred to.

Scandinavia exhibits the largest continuous tract of pre-Cambrian rocks in Europe.[4]

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[1] J. Phillips, 'Geology of the Malvern Hills,' *Mem. Geol. Surv.* ii. part 1 ; Holl, *Quart. Journ. Geol. Soc.* xxi. p. 72 ; Rutley, *op. cit.* xliii. (1887) 481 ; Callaway, p. 525, *op. cit.* xlv. (1889) p. 475.

[2] *Quart. Journ. Geol. Soc.* xxxiii. (1877) p. 754, xxxiv. (1878) p. 199, xxxvi. (1880) p. 337, xlvii. (1891) p. 78.

[3] Lapworth, *Geol. Mag.* (1886) p. 321 ; T. H. Waller, *op. cit.* p. 323 ; Rutley, p. 557.

[4] In the older literature consult Keilhau, 'Gaea Norvegica,' iii. (1850). Kjerulf, 'Udsigt over det Sydlige Norges Geologi,' Christiania, 1879 (translated into German by Gurlt, and published by Cohen, Bonn, 1880). A. E. Tornebohm, "Die Schwedischen Hochgebirge," *Schwed. Akad.* Stockholm, 1873. "Das Urterritorium Schwedens," *Neues Jahrb.* 1874, p. 131. Karl Pettersen, "Geologiske Undersogelser inden Tromso Amt," &c., *Norske Videnskab. Skrift*, vi. 44 ; vii. 261. For more recent work see Reusch's important monograph on the fossiliferous crystalline schists of Bergen, quoted on p. 621, also his instructive essay 'Bömmelöen og Karmoen,' 1888 ; his papers in the 'Aarbog for 1891' of the Geological Survey of Norway (*Norges Geologiske Undersögelse*) ; his 'Geologiske Iagttagelser fra Trondhjems Stift,' *Christiania vidensk. selsk. forhandl.* 1891 ; and his paper on crystalline schists of Western Norway, *Compt. rend. Congrès Géol. Internat.* 1888 (1891), p. 192. T. Dahll, O. A. Corneliussen, and H. Reusch, 'Det nordlige Norges geologi,' *Norges Geolog. Undersög.* 1892 ; C. H. Homan, 'Selbu,' *Norges Geolog. Undersog.* 1890 ; and Törnebohm, *Nature*, 1888, p. 127. It is to be hoped that Professor Brögger may be able to attack the problem of the schistose rocks of Norway, and that we may have from him such a detailed study of them as he has given us in his memoirs on the Christiania district.

Although these rocks have been more or less minutely examined throughout the whole extent of the peninsula, and have been described in many papers and memoirs, the published descriptions of them, though often excellent from the lithological point of view, were almost entirely written before the recent revolution in the views of geologists regarding metamorphism, and are therefore without that knowledge of the true meaning of structural characters and that detailed study of the tectonic relations of the rocks which the present condition of the science demands. There can be no doubt that the older crystalline rocks of Scandinavia are a prolongation of those which farther to the south-west rise out of the Atlantic in the Highlands of Scotland and the hills of the north and west of Ireland. And there seems every probability that the broad features of geological structure which have been ascertained to prevail in the British area will be found to extend also into Norway and Sweden.[1]

Wide tracts of western Norway consist of coarse banded gneisses (Grundfjeldet, Urberget), which present the closest resemblance to the Lewisian series of Sutherland and Ross, but with a wider range of petrographical diversity. They include red and grey gneisses, banded and streaked granulites, epidote-gneiss, cordierite-gneiss, granites, syenites, gabbros, diorites, labradorite-rocks, garnet-rocks, amphibolites, peridotites, serpentines, &c. The general assemblage of these rocks suggests that they represent a complex series of acid and basic eruptive masses. With them is intimately associated another group of rocks, of which conspicuous members are quartzite, limestone, mica-schist, quartz-schist, and others which point with more or less clearness to a sedimentary origin. This group is usually quite crystalline, and is certainly older than some portions of the gneisses which can be seen to pierce it. It contains, however, bands of amphibolite, which may represent sills intruded between its component layers. Thus at Rukedal (Southern Norway) a mass, 3900 feet thick, of quartzite, quartz-schist, and interbedded seams of hornblende-schist, lies upon a group of hornblende-schists and grey gneiss traversed by abundant granite veins. Thin bands of limestone occasionally occur in the gneiss, as near Christiansand, where they have yielded many minerals, especially vesuvianite, coccolite, scapolite, phlogopite, chondrodite, and black spinel. Apatite with magnetite, titaniferous iron, hæmatite, and other ores forms a marked feature of the Norwegian pre-Cambrian series. The most important mineral masses in an industrial sense are thick beds and lenticular masses of iron-ore (Dannemora, Filipstad, &c.)

Of obviously later date than the coarse gneisses with their accompaniments is another series of crystalline schists which spreads over vast tracts of country in Scandinavia. Among these rocks mica-schists, phyllites, quartz-schists, clay-slates, quartzites, and schistose conglomerates are conspicuous, and indicate that a large proportion of the whole mass is probably of clastic origin. But there are also included chloritic and hornblende schists, amphibolites, gneisses, and many other rocks which were probably of eruptive origin, whether injected as sills or thrown out contemporaneously with the sedimentation of the schists as tuffs and lavas. In many respects this important series of schists bears a close resemblance to the "younger gneiss" and Dalradian rocks of Scotland. But its actual stratigraphy has not yet been accurately elucidated. That some portion of it may be pre-Cambrian seems sufficiently probable. But its true relations are complicated by the discovery of Silurian fossils in some portions of the series and by the apparent gradation of comparatively unaltered fossiliferous Silurian strata into the schistose condition. Dr. Hans Reusch of the Geological Survey of Norway has shown that among the crystalline schists to the south of Bergen bands of fine mica-schist or phyllite with layers and nodules of limestone contain fossils probably of Upper Silurian age.[1] I have had an opportunity of visiting the district described by him, have collected fossils from all the localities which he enumerates, and can entirely confirm the account which he gives of the thoroughly metamorphic character of the rocks among which the fossiliferous bands occur. The phyllites are intercalated among white quartzites, quartzite conglomerates, green schists, hornblendic and actinolitic schists and gneisses. But for the occurrence of the fossils, a geologist would naturally class the rocks as probably of pre-Cambrian age. But the corals, graptolites, and other organic remains make it quite certain that the crystalline schists in which they occur underwent their great metamorphism not earlier than some part of the Upper Silurian period. It will be an extremely difficult and laborious task to disentangle the complications of these Norwegian rocks, and to determine which are of pre-Cambrian and which of Palæozoic age. Dr. Reusch, summing up what is known regarding the distribution of fossils among these strata, believes that a more or less continuous belt of Cambrian and Silurian rocks, usually in an extremely metamorphosed condition, can be traced along the axis of the Scandinavian peninsula from near Stavanger to the North Cape.[2] That in this region there were gigantic terrestrial movements with concomitant faults, over-thrusts and metamorphism after Lower Silurian times, is abundantly evident. In southern Norway and in Sweden enormous masses of crystalline schists actually overlie the oldest fossiliferous rocks, as will be described in later pages (p. 769).

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[1] As the result of two journeys in Norway from Bergen to Hammerfest I was convinced of this general parallelism, but the determination of the detailed stratigraphy of the country will be a task of incredible labour demanding from the Scandinavian geologists many years of patient application.

In the east and south of Norway a thick mass of reddish and greyish felspathic sandstone, known there as *Sparagmite*, intervenes between the oldest gneisses (Urberget) and the base of the Cambrian series. It is associated with quartzite and shales, and sometimes becomes strongly conglomeratic. It recalls the Torridon sandstone of Scotland. Probably a large mass of strata, belonging to distinct geographical periods, has been grouped together under the common name of sparagmite. The older sparagmite which underlies the *Olenellus*-zone is probably pre-Cambrian. In western and northern Norway, where the crushing and metamorphism have been so intense, the sparagmite is not recognisable, though it may in an altered condition extend through these regions.

In southern and central Sweden three or four groups of stratified formations, attaining a united thickness of many thousand feet, have been recognised as intermediate between the old gneiss and the lowest portions of the Cambrian system. Their relations to each other have not been very satisfactorily determined, some of them having only a local development. They are distinguished by the following names :—

Visingsö group.—Sandstones, red and green shales, limestone, and conglomerates. 300 metres. Visingsö on Lake Wettern.

Almesåkra group (near Lake Wettern) and Dala Sandstone.—Red and white sandstones and quartzites, sparagmite, red shales, and rarely limestone. The Dala Sandstone is believed by Tornebohm to spread over an area of 7150 square kilometres. It attains a thickness of sometimes nearly 900 metres, and contains in the south two well-marked sheets of diabase.

Dalsland group.—Seen in Dalsland only, and composed of an upper group of shales or slates lying on a quartzite series, below which lies a lower shaly series followed by a thick group of sandstones and coarse conglomerates. The total thickness according to Törnebohm is 1900 metres.

Central Europe.—From Scandinavia, a great series of crystalline schists presumed to be pre-Cambrian ranges through Finland[3] into the north-west of Russia, re-appearing in the north-east of that vast empire in Petchora Land down to the White Sea, and rising in the nucleus of the chain of the Ural Mountains, and still farther south in Podolia. In Central Europe, similar rocks appear as islands in the midst of more recent formations. Among the Carpathian Mountains, they protrude at a number of points. Westwards of the central portion of the Alpine chain, they rise in a more continuous belt, and show numerous mineralogical varieties, including gneiss, mica-schist, and many other schists, as well as limestone and serpentine. Some of these rocks are certainly altered sedimentary deposits, others are probably crushed igneous rocks. The protogine of the Alps has been shown by Michel Lévy to be intrusive. It behaves to the surrounding schists as some parts of the Laurentian gneiss of Canada do to the schists next to that rock.

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[1] 'Silurfossiler og pressede Konglomerater i Bergensskifrene,' 1882 ; translated into German by R. Baldauf with the title 'Die fossilien-fuhrenden krystallinischen Schiefer von Bergen,' Leipzig, 1883.

[2] See his sketch-map of Norway and Finland (Geologisk Kart over de Skandinaviske Lande og Finland), Christiania, 1890.

[3] The petrographical characters of the vast area of ancient gneiss in Finland are now

Pre-Cambrian rocks rise to the surface in a number of detached areas in France, particularly in Brittany, the Cotentin, the central plateau, Morvan, Cevennes, the Pyrenees, the Dauphiny Alps, and the Vosges. In Brittany they have recently been carefully studied by Dr. Barrois, who describes them as largely composed of mica-schists, passing often into gneiss and into quartzite, and including chlorite-schists, amphibolites, talcose and sericitic schists, serpentines, eclogites, and pyroxenites.[1] Extensive masses of granitoid and granulitic gneisses with mica-schists, amphibolites and other crystalline rocks form the foundation of the great central plateau of France. In Brittany, in the central plateau, as well as in other regions of France, thick masses of slates and phyllites occur which by some writers have been placed in the pre-Cambrian series. In the Cotentin they are represented by the "Phyllades de St. Lô"—a thick series of hard lustrous slates or phyllites, among which tracks of annelides (?) have been found. By other geologists, however, these rocks are placed in the Cambrian system.

A large area of ancient crystalline schists extends southward from Dresden through Bavaria and Bohemia between the valley of the Danube and the headwaters of the Elbe. Two well-marked groups have been recognised—(*a*) red gneiss, containing pink orthoclase and a little white potash-mica, covered by (*b*) grey gneiss, containing white or grey felspar, and abundant dark magnesia-mica. According to Gümbel the former (called by him the Bojan gneiss) may be traced as a distinct formation associated with granite, but with very few other kinds of crystalline or schistose rocks, while the latter (termed the Hercynian gneiss) consists of gneiss with abundant interstratifications of many other schistose rocks, graphitic limestone, and serpentine. The Hercynian gneiss is overlain by mica-schists, above which comes a vast mass of argillaceous schists and shales. In Bohemia, these overlying crystalline clay-slates and schists ("Étage A" of Barrande) graduate upward into undoubted clastic rocks known as the Pribram Shales, unconformably over which come conglomerates and sandstones lying at the base of the fossiliferous series.[2] The same gradation occurs around the granulite tract of Saxony, where the outer schists may be merely metamorphosed Palæozoic sedimentary rocks.[3]

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being carefully mapped and described by the Geological Survey of that country under K. A. Moberg. Each sheet of the map, of which twenty-one have been published up to the present time (July 1893), is accompanied by an explanatory pamphlet.

[1] *Ann. Soc. Géol. Nord*, x. xiv. xvi.

[2] For descriptions of the pre-Cambrian rocks of Saxony see Credner, *Zeitsch. Deutsch. Geol. Ges.* 1877, p. 757; explanations accompanying the sheets of the Geological Survey Map of Saxony, particularly sections Geringswalde, Geyer, Glauchau, Hohenstein, Penig, Rochlitz, Schwarzenberg, Waldheim, Wiesenthal. Bavaria and Bohemia: Gümbel, 'Geognostische Beschreibung des Ostbayerischen Grenzgebirges,' Gotha, 1868; Jokely, *Jahr. Geol. Reichsanstalt*, vi. p. 355; viii. pp. 1, 516; Kalkowsky, 'Die Gneissformation des Eulengebirges' (Habilitationschrift), Leipzig, 1878; *Neues Jahrb.* 1880 (i.) p. 29. F. Katzer, 'Geologie von Böhmen,' 1892.

[3] Lehmann, 'Entstehung der altkrystallinischen Schiefergesteine,' 1884.

In the central Pyrenees pre-Cambrian granites, with associated well-stratified masses of gneiss, mica-schist, limestone, &c., are said to occur, but possibly some at least of these rocks are altered Cambrian slates.[1] In Asturias and Gallicia, Barrois has investigated a great series of schists regarded by him as pre-Cambrian, and divisible into two important groups—a lower, composed essentially of mica-schists, and an upper, consisting of green chloritous, amphibolitic, talcose or micaceous schists, with subordinate bands of quartzite, serpentine, and cipoline.[2]

America.—In North America the pre-Cambrian rocks, which cover an area estimated at more than 2,000,000 square miles, from the Arctic Ocean southwards to the great lakes, have been studied in detail for a longer period than those of any other region, and in many respects they may serve as the type with which those of other parts of the globe may be compared. They were first mapped and described by Logan and Murray in Canada, and were divided by these observers into two distinct divisions. The lower of these, named Laurentian from its extensive development among the Laurentide mountains, was described as consisting chiefly of coarse red, grey, and banded felspathic, hornblendic, micaceous, and pyroxenic gneisses with pegmatites, and included zones of limestone. The upper group, called Huronian from its exposures in the Lake Huron district, was recognised as being composed mainly of quartzites, felsites, diorites, diabases, syenites, various coarse and fine fragmental volcanic rocks (agglomerates and tuffs), clay-slates, and other bedded materials that passed into schists. Though the Huronian series was found along the line of junction to dip below the Laurentian, this position was believed to be due to disturbance, no doubt being entertained that the former series was the younger of the two.

Since the days of these two great pioneers of American pre-Cambrian geology the subject has been attacked by many able observers. The Geological Surveys of Canada and the United States, as well as those of some of the States of the Union, particularly Michigan, Wisconsin, and Minnesota, have examined the rocks over many hundred square miles, and have published voluminous reports concerning them. Unfortunately as many of the districts were worked out independently, considerable variety of nomenclature and diversity of view have arisen. At present it is hardly possible to reconcile these conflicting opinions, though there can be little doubt that before long a general concurrence will be arrived at regarding the main features of pre-Cambrian geology in this important region. The table on the next page gives the subdivisions which appear to be best established in the Lake Superior and Lake Huron territory.[3]

According to the general consensus of opinion among the present geologists of the United States and of Canada, the pre-Cambrian rocks of those countries may be divided into two great series. At the base lies a vast mass of gneisses, schists, and eruptive rocks, which, known as the "Fundamental Complex," is regarded as the oldest of the whole. Above this ancient series comes another enormous succession of rocks comprised under the general name of "Algonkian," but consisting of several distinct formations, separated from each other by unconformabilities, as shown here in the table.[4]

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[1] Garrigou, *Bull. Soc. Géol. France*, i. (1873) p. 418.

[2] *Ann. Soc. Géol. Nord*, ii. (1882).

[3] In compiling this table I have been indebted to Mr. C. R. van Hise of the United States Geological Survey for information kindly supplied by him, also to his paper in the *Amer. Journ. Sci.* and to Mr. Lawson's 'Report on the Rainy Lake Region' in the Annual Report of the Canadian Geological Survey for 1887.

[4] Out of the large amount of literature which has grown up concerning the pre-Cambrian rocks of North America the following works may be cited:—W. E. Logan, 'Geology of Canada,' 1863; *Annual Reports of the Geological Survey of Canada*, particularly Mr. Lawson's Report on Rainy Lake above cited; *Geological and Natural History Survey of Minnesota*, vol. ii. Geology, by N. H. Winchell and W. Upham, 1888, and Annual Reports for 1887, 1888, 1891; *Geological Survey of Wisconsin*, Final Reports, vols. i. ii.

TABLE OF THE SEQUENCE OF THE PRE-CAMBRIAN FORMATIONS OF THE UNITED STATES AND CANADA.

Algonkian	Keweenawan [Nipigon of W. Ontario].	Detrital rocks derived in large measure from the degradation of the volcanic series below, 15,000 feet. Sheets of basic and acid lavas, with intercalated masses of sandstone and conglomerate, especially towards the upper part. Said to reach a thickness of 35,000 feet or more than 6½ miles (?).
		[Unconformability.]
	Upper (original) Huronian [Animikie and Upper Kaministiquia of W. Ontario, Animikie and Upper Vermilion of N. Minnesota, Upper Marquette of Michigan].	Quartzites, carbonaceous and argillaceous shales, slates, conglomerates and ferruginous rocks with intrusive greenstones, at least 12,000 feet. Traces of organisms occur in this series.
		[Unconformability.]
	Lower Huronian [Keewatin, Lower Kaministiquia, Ontario, Lower Vermilion of N. Minnesota, Lower Marquette, Felch Mountain iron-bearing series, Menominee of Michigan].	Limestones, quartzites, phyllites, slates, mica-schists, green chloritic schists, schistose conglomerates, jaspers, iron-ores, diabase and quartz-porphyry lavas, volcanic agglomerates and tuffs with acid and basic intrusions. Probably more than 5000 feet.
		[Unconformability.]
Fundamental Complex.	Coutchiching.	Quartz-biotite mica-schists and fine grey gneisses of remarkably uniform character, estimated by Lawson to be more than 20,000 feet thick in some places, but elsewhere thinner and disappearing.
	Laurentian.	Hornblende-granites and syenites, coarse granitic gneisses and biotite gneisses, some of which have been intruded into the quartz-biotite schists, and even into the base of the group above them.

Mr. Lawson, in his remarkable essay on the Geology of the Rainy Lake region, has brought forward conclusive proof that the Laurentian gneisses invade and alter his Coutchiching schists, and even penetrate in some places into his Keewatin series above. He believes that these gneisses arose from the fusion of the basement or floor on which the overlying formation rested, portions having been absorbed into the magma, and finally appearing with it as gneiss. More recently Messrs. Pumpelly and Van Hise have found on the north shore of Lake Huron clear evidence that the base of

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iii. iv. by T. C. Chamberlin, R. D. Irving, C. E. Wright, E. T. Sweet, T. B. Brooks, &c. ; *Geological Survey of Michigan*, 1873 (T. B. Brooks), 1881, vol. iv. (C. Rominger), 1891-92, containing a sketch of the geology of the iron, gold, and copper districts by M. E. Wadsworth ; *Second Geological Survey of Pennsylvania*, summary volume on Archæan Rocks by J. P. Lesley, 1892 ; *Annual Reports of the United States Geological Survey*, especially the 5th and 7th, containing memoirs by R. D. Irving, and the 10th containing a joint memoir by R. D. Irving and C. R. van Hise, and monograph V., on the copper-bearing rocks of Lake Superior by R. D. Irving ; *Bull. U.S. Geol. Surv.* No. 23, T. C. Chamberlin and R. D. Irving ; A. C. Lawson, *Bull. Geol. Soc. Amer.* i. (1890) pp. 163, 175 ; A. Winchell, *op. cit.* i. p. 357, ii. p. 85 ; N. H. Winchell, *Proc. Amer. Assoc.* xxxiii. (1885) ; J. D. Whitney and M. E. Wadsworth, 'The Azoic System,' *Bull. Mus. Comp. Zool.* Harvard, 1884. C. R. van Hise, *Amer. Journ. Sci.* xli. (1891) 117 ; R. Pumpelly and C. R. van Hise, *op. cit.* xliii. (1892) p. 224. The literature of American pre-Cambrian geology has recently been exhaustively discussed by C. R. van Hise in *Bull. U.S. Geol. Surv.* No. 86, 'Correlation Papers—Archæan and Algonkian,' 1892.

the Lower Huronian rocks is marked by a coarse conglomerate lying with a complete unconformability upon and made up out of the schists, granites, and pegmatites of the fundamental complex.[1]

India.—In India, the oldest known rocks are gneisses which underlie the most ancient Palæozoic formations, and appear to belong to two periods. The older or Bundelkund gneiss is covered unconformably by certain "transition" or "submetamorphic" rocks, which, as they approach the younger gneiss, become altered and intersected by granitic intrusions. The younger or peninsular gneiss is therefore believed to be a metamorphic series unconformable to the older gneiss. In the western Himalayan chain there are likewise two gneisses—a central gneiss, probably Archæan, and an upper gneiss formed by the metamorphism of older Palæozoic rocks into which it passes, and which lie unconformably on the older gneiss and contain abundant fragments derived from it.[2]

China.—Pre-Cambrian rocks are extensively developed in northern China, forming the fundamental masses round and over which the later rocks have been laid down. According to Richthofen, the oldest portions of the series are mica-gneisses and gneiss-granites with hornblende-schists, mica-schists, &c., having an N.N.W. strike and steep inclination. Apparently of later date are some chlorite-gneisses and hornblende-gneisses with intercalations of mica-gneiss and granulite, but without gneiss-granite, seen in north Tshili and north Shansi, and marked by a persistent W.S.W. and E.N.E. strike. These rocks are succeeded unconformably by a great series of groups which may belong to distinct periods. They consist of mica-schists, crystalline limestones, black quartzites, hornblende-schists, coarse conglomerates and green schists. With some of these groups are associated granite, pegmatite, syenite, and diorite. The whole series underwent great plication and denudation before the deposition of the older Palæozoic formations (Sinisian).[3]

Australasia.—In the South Island of New Zealand, the most ancient Palæozoic rocks are underlain by vast masses of crystalline foliated rocks traceable nearly continuously on the west side of the main watershed. The geological relations of these masses have not yet been satisfactorily defined, and it does not appear to be established whether any portion of them are undoubtedly pre-Cambrian. They are divided by Sir J. Hector into two series, of which the lower consists of gneiss, granite, &c., with an overlying mass of hornblendic, micaceous, and argillaceous schists (probably metamorphosed Devonian); while the upper consists of argillaceous slates and schists, which are regarded as probably altered Silurian or even Carboniferous rocks.[4] In Canterbury there is a central zone of micaceous, talcose, and graphitic schists, overlain by chlorite and hornblende-schists, and lastly by a quartzitic zone interleaved with schists.[5] Crystalline schists and gneisses form the rugged mountainous ground of south-western Otago. The centre of this province is occupied by a broad band of gently inclined mica-schists and slates. These rocks are the main gold-bearing series of Otago.[6]

In Australia, large areas of granite and of crystalline schists occur, but their precise relations have not yet been worked out. Some of these rocks have been described by Selwyn, Ulrich, R. L. Jack, R. A. F. Murray, and others, as probably including metamorphosed Palæozoic formations. But there are not improbably portions of them referable to a pre-Cambrian series.

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[1] *Amer. Journ. Sci.* xliii. (1892) p. 224.

[2] Medlicott and Blanford, 'Manual of Geology of India,' pp. xviii. xxvi. But there are younger Indian schistose rocks, from which these must be distinguished. In the Himalayan region there is a series of gneisses and schists below which lie comparatively unaltered beds of supra-Triassic age.

[3] Richthofen, 'China,' ii. (1882).

[4] 'Handbook of New Zealand,' by J. Hector, M.D., Wellington, 1883.

[5] Haast's 'Geology of Canterbury,' p. 252.

[6] Hutton's 'Geology of Otago,' p. 31.

PART II. PALÆOZOIC.

It has been shown in the foregoing pages that though the stratified pre-Cambrian rocks are generally separated by an unconformability from formations of later age, such a break does not always occur, and that in its absence no sharp line of division can be drawn by way of upward limit to the pre-Cambrian series. It is obvious that the physical conditions of sedimentation underwent no universal interruption at the close of pre-Cambrian time, that these conditions had already been established long before the Cambrian period, and that they were continued in some regions into that period without a break. Moreover, it has now been ascertained beyond doubt that plant and animal life had already appeared upon the earth during pre-Cambrian time. Hence the term Palæozoic, or Primary, which has hitherto been used to denote the older fossiliferous systems that terminate downward at the base of the Cambrian rocks is no longer strictly accurate, unless it is extended so as to include the very oldest strata in which organic remains have been found. Geologists have agreed to fix the base of the Cambrian system at the *Olenellus*-zone, already referred to. It is quite evident, however, that at any moment a new series of fossils may be discovered below that horizon, and it will then be matter for consideration whether such a series should be included in the Cambrian fauna or be made the palæontological basis for the designation of a still older geological system. In the present meagre state of our knowledge regarding these ancient rocks, it seems the most prudent course to take in the meantime the platform of the *Olenellus*-zone, which has now been recognised in many parts of the globe, as the Cambrian basement, and to fix there provisionally the downward limit of the Palæozoic series of systems. That series will thus include all the older sedimentary formations from the bottom of the Cambrian to the top of the Permian system. The strata embraced under the comprehensive designation of Palæozoic consist mainly of sandy and muddy sediments with occasional intercalated zones' or thick masses of limestone. They seem everywhere to bear witness to comparatively shallow water and the proximity of land. Their frequent alternations of sandstone, shale, conglomerate, and other detrital materials, their abundant rippled and suncracked surfaces, marked often with burrows and trails of worms, as well as the prevalent character of their organic remains, show that they must generally have been deposited in areas of slow subsidence, bordering continental or insular masses of land. From the character of the organisms preserved in them, the Palæozoic rocks, as far as the present evidence goes, may be grouped into two main divisions—an older and a newer:—the former, or Silurian facies (from the base of the Cambrian to the top of the Silurian system), distinguished more especially by the abundance of its graptolitic, trilobitic, and brachiopodous fauna, and by the absence of vertebrate remains; the latter, or Carboniferous facies (from the top of the Silurian to the top of the Permian system), marked by the number and variety of its fishes and amphibians, the disappearance of graptolites and trilobites, and the abundance of its cryptogamic terrestrial flora.

Section i. Cambrian (Primordial Silurian).

§ 1. General Characters.

In those regions of the world where the relations of the pre-Cambrian to the oldest unmetamorphosed Palæozoic rocks are most clearly exposed and have been most carefully studied, it is seldom that any conformable passage can be traced between these two great rock-groups, though, as already stated, occasional examples of such a gradation occur. More usually a marked unconformability and strong lithological contrast have been observed between the two series, the younger frequently abounding in pebbles derived from the waste of the older. Such a break points to the lapse of a vast interval of time during which the pre-Cambrian rocks, after suffering much crumpling and metamorphism, were ridged up into land and were then laid open to prolonged denudation. These changes seem to have been more especially prevalent in the northern part of the northern hemisphere. At all events, there is evidence of extensive upheaval of land in the north-west of Europe and across the northern tracts of North America and Northern China[1] prior to the deposit of the earliest remaining portions of the Palæozoic formations. These strata, indeed, were derived from the degradation of that northern land, the extent and height of which may be in some measure realised from the enormous piles of sedimentary rock which have been formed out of its waste. To this day, much of the land in the boreal tracts of the northern hemisphere still consists of pre-Cambrian gneiss. We cannot affirm that the primeval northern land was lofty; but, if it was not, it must have been subjected to repeated renewals of elevation, to compensate for the loss of height which it suffered in the denudation that provided material for the deep masses of Palæozoic sedimentary rock.

The earliest connected suite of deposits in the Palæozoic series received the name "Cambrian," from Sedgwick who with great skill unravelled the stratigraphy of the most ancient sedimentary rocks of North Wales (Cambria). When the peculiar brachiopodous and trilobitic fauna of Murchison's Silurian system was found to descend into these rocks, the term Primordial Zone or Primordial Silurian was applied to them by Barrande in Bohemia. For many years, however, they yielded so few fossils that their place as a distinct section of the geological record was disputed. Eventually by the labours of Barrande in Bohemia; Hicks in South Wales; Brögger, Linnarsson, and others in Scandinavia; Schmidt in the Baltic provinces of Russia; Billings, Mathew, Walcott, and others in Canada and the United States, as well as various workers in other countries—such a distinctive fauna has been brought to light as serves to characterise a series of deposits at the base of the Palæozoic formations. This assemblage of fossils, Barrande's first or Primordial fauna, is now by common consent more commonly known as Cambrian. The use of the terms Cambrian and Silurian will be more fully referred to in later pages.

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[1] The vast erosion of the pre-Palæozoic land is nowhere more impressively shown than in Northern China, where, as Richthofen has pointed out, the oldest gneisses are surmounted by thousands of feet of sedimentary material (Sinisian formation), in the uppermost parts of which Primordial fossils are found. 'China,' vol. ii.

ROCKS.—The rocks of the Cambrian system present considerable uniformity of lithological character over the globe. They consist of grey and reddish grits or greywackes, quartzites and conglomerates, with shales, slates, phyllites or schists, and sometimes thick masses of limestone. Their false-bedding, ripple-marks, and sun-cracks indicate deposit in shallow water and occasional exposure of littoral surfaces to desiccation. Sir A. C. Ramsay suggested that the non-fossiliferous red strata may have been laid down in inland basins, and he speculated upon the probability even of glacial action in Cambrian time in Britain.[1] As might be expected from their high antiquity, and consequent exposure to the terrestrial changes of a long succession of geological periods, Cambrian rocks are usually much disturbed. They have often been thrown into plications, dislocated, placed on end, cleaved, and metamorphosed. In Wales they include towards their base an interesting volcanic group consisting of felsitic and diabase-tuffs, and olivine-diabase in interbedded sheets, through which eruptive acid rocks (quartz-felsites, &c.) have risen.

LIFE.—Much interest necessarily attaches to Cambrian fossils, for excepting the few and obscure organic remains obtained from pre-Cambrian strata, they are the oldest assemblage of organisms yet known. They form no doubt only a meagre representation of the fauna of which they were once a living part. One of the first reflections which they suggest is that they present far too varied and highly organised a suite of organisms to allow us for a moment to suppose that they indicate the first fauna of our earth's surface. Unquestionably they must have had a long series of ancestors, though of these still earlier forms such slight traces have yet been recovered.[2] Thus, at the very outset of his study of stratigraphical geology, the observer is confronted with a proof of the imperfection of the geological record. When he begins the examination of the Cambrian fauna, so far as it has been preserved, he at once encounters further evidence of imperfection. Whole tribes of animals, which almost certainly were represented in Cambrian seas, have entirely disappeared, while those of which remains have been preserved belong to different and widely separated divisions of invertebrate life.

The prevailing absence of limestones from the Cambrian deposits of western Europe is accompanied by a failure of the foraminifera, corals, and other calcareous organisms which abound in the limestones of the next great geological series.[1] The character of the general sandy and muddy sediment must have determined the distribution of life on the floor of the Cambrian sea in that region, and doubtless has also affected the extent of the final preservation of organisms actually entombed. In North America, on the other hand, where thick sheets of Cambrian limestone occur, the conditions of sedimentation have been far more favourable for the preservation of organic forms; hence the known Cambrian fauna of this region exceeds in numerical value that of Europe.

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[1] *Q. J. Geol. Soc.* xxvii. (1871) p. 250; *Proc. Roy. Soc.* xxiii. (1874) p. 334; *Brit. Assoc.* 1880, Presidential Address.

[2] Richthofen has suggested that in China possibly some of the deep parts of his "Sinisian" formation (which in its higher parts yields Primordial fossils) may yet reveal traces of still older faunas.

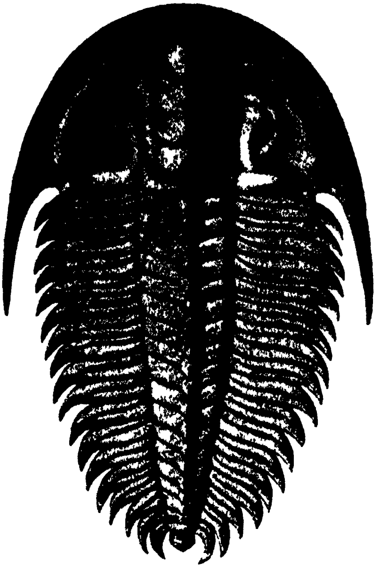

Fig. 336.—Olenellus (O Callavei, restored by Lapworth) the characteristic genus of the lowest Cambrian strata (½).

The plants of the Cambrian period have been scarcely at all preserved. No vestige of any land plant of this age has yet been detected. That the sea then possessed its sea-weeds, can hardly be doubted, and various fucoid-like markings on slates and sandstones (*e.g.* the so-called fucoids of the "fucoid-beds" of N.W. Scotland, and of the "fucoidal sandstone" of Scandinàvia) have been referred to the vegetable kingdom. The genus *Eophyton*[2] from Sweden, and others from the Potsdam sandstone of North America, have been described as plants. There seems to be little doubt, however, that of these various markings some are tracks, probably of worms, others are merely imitative wrinkles and markings of inorganic origin.[3] It is not certain that any of them are truly plants. What has been regarded as an undoubted organism occurs in abundance in the Cambrian rocks of the south-east of Ireland, and is named *Oldhamia* (Fig. 338). For many years it was considered to be a sertularian zoophyte, subsequently it was referred to the calcareous algæ; but its true grade seems still uncertain.[4]

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[1] In the Baltic basin some bands of limestone occur in the comparatively thin series of Cambrian strata. In Scotland the Cambrian system includes some 1500 feet of limestone.

[2] See G. J. Hinde, *Geol. Mag.* 1886, p. 337; the "fucoids" of the "fucoid-beds" of N.W. Scotland are undoubtedly worm-casts.

[3] See A. G. Nathorst's essay, "Nouvelles observations sur des traces d'Animaux, etc." 4to, Stockholm, 1886.

[4] Its claim to be considered organic has even been disputed, but from the manner in which it occurs on successive thin laminae of deposit I cannot doubt that it is really of organic origin.

Among the animal organisms of the Cambrian rocks the most lowly forms yet detected are hexactinellid sponges, *Protospongia*[1] (Fig. 338), *Leptomytus*, *Trachyum*. The hydrozoa appear in the earliest forms of the tribe of graptolites which played such an important part in Silurian time. Of the Cambrian types, *Dictyograptus* (*Dictyonema*) is one of the most characteristic fossils of the primordial zone of Scandinavia, and other forms are doubtfully referred to *Phyllograptus*, *Climacograptus*, and *Dactyloidites*. Casts which are regarded as those left by medusae on the soft mud of the sea-shore, have been noticed in Scandinavia. The Actinozoa of the Cambrian period occur in a number of early types of corals referred to *Archæocyathus*,[3] *Ethmophyllum* and *Spirocyathus*. The Echinodermata are represented by crinoids (*Dendrocrinus*), cystideans (*Protocystites*, Fig. 338, *Eocystites*), and star-fishes (*Palæasterina*, Fig. 339). The crinoids reached their culmination in a variety of forms during

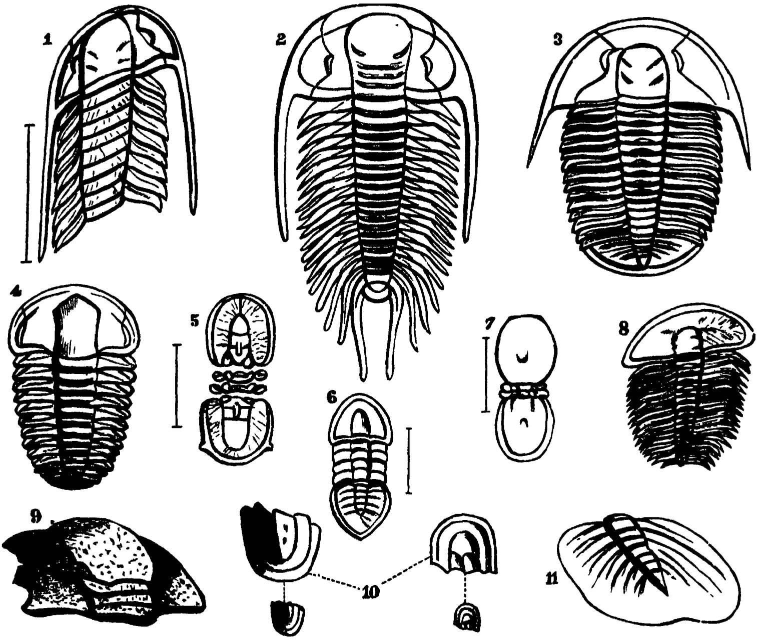

Fig. 337.—Group of Cambrian Trilobites[2]

1, Olenus impar, Salt. (enlarged); 2, Paradoxides Davidis, Salt. ($\frac{1}{10}$); 3, Conocoryphe (?) Williamsoni, Belt.; 4, Ellipsocephalus Hoffi, Schloth.; 5, Agnostus princeps, Salt. (enlarged); 6, Microdiscus sculptus, Hicks (enlarged); 7, Agnostus Barlowii, Belt. (enlarged); 8, Erinnys venulosa, Salt.; 9, Plutonia Sedgwickii, Hicks; 10, Agnostus cambrensis, Hicks (and enlarged); 11, Dikelocephalus celticus, Salt.

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[1] For a description of the character of this earliest sponge, see Sollas, *Q. J. Geol. Soc.* xxxvi. (1880) p. 362.

[2] Where not otherwise stated the figures are of the natural size.

[3] Hinde, *Quart. Journ. Geol. Soc.* xlv. (1889) p. 125.

Palæozoic time. Though still enormously abundant in individuals on some parts of the present sea-floor, they are but poorly represented there compared with the profusion of their genera and species in the earlier periods of the earth's history. Palæozoic crinoids were distinguished by the vaulted arrangement of accurately fitting plates, by which their viscera were completely enclosed, after the manner of the sea-urchins. The cystideans were so named from the bag-like form in which the polygonal plates enclosing them are arranged.

That annelides existed during the Cambrian period is shown by their frequent trails and burrows (*Arenicolites*, Fig. 338, *Cruziana*, *Scolithus*, *Planolites*, &c.) But the most abundantly preserved forms of life are crustacea, chiefly belonging to the extinct order of trilobites (Figs. 336, 337). It is a suggestive fact that these organisms appear even here, as it were, on the very threshold of authentic biological history, to have reached their full structural development. Some of them, indeed, were of dimensions scarcely ever afterwards equalled, and already presented great variety of form. Individuals of the species *Paradoxides Davidis* are sometimes nearly two feet long. But with these giants were mingled other types of diminutive size. It is noteworthy also, as Dr. Hicks has pointed out, that while the trilobites had attained their maximum size at this early period, they were represented by genera indicative of almost every

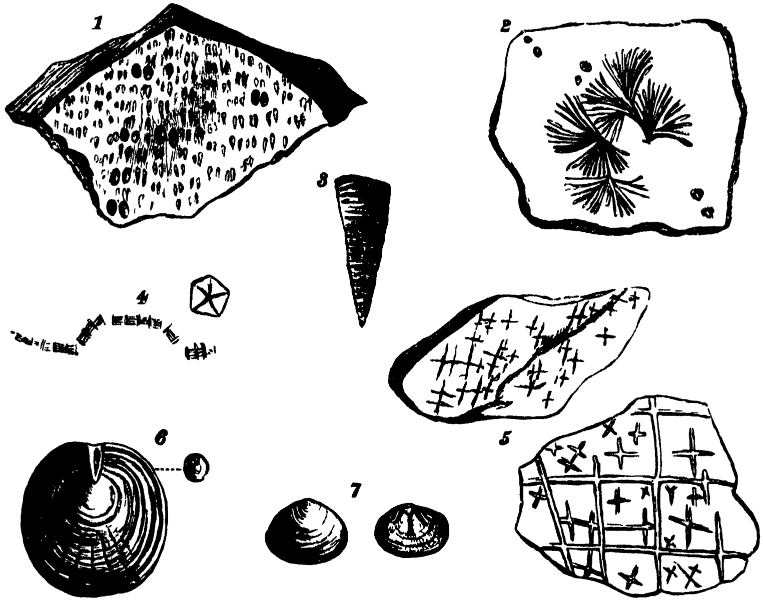

Fig. 338.—Group of Cambrian Fossils.

1, Arenicolites didymus, Salt.; 2, Oldhamia antiqua, Forbes; 3, Theca corrugata, Salt.; 4, Protocystites menevensis, Hicks ($\frac{2}{1}$); 5, Protospongia fenestrata, Salt. (and enlarged $\frac{4}{1}$); 6, Discina pileolus, Hicks (and enlarged); 7, Obolella maculata, Hicks.

stage of development, "from the little *Agnostus* with two rings in the thorax, and *Microdiscus* with four, to *Erinnys* with twenty-four," while blind genera occurred, together with those having the largest eyes.[1] In the lower portions of the system the genus *Olenellus* (Fig. 336) is especially distinctive. Other characteristic Cambrian genera (Fig. 337) besides those already mentioned are *Plutonia*, *Ellipsocephalus*, *Conocoryphe* (*Conocephalites*), *Anomocare*, *Agraulos*, *Ptychoparia*, *Solenopleura*, *Dikelocephalus*, *Olenus*, *Olenoides*, and *Anopolenus*. Phyllopod crustaceans likewise occur (*Hymenocaris*, Fig. 339, *Aristozoe*), and there are likewise representatives of the living order of ostracods (*Leperditia*).

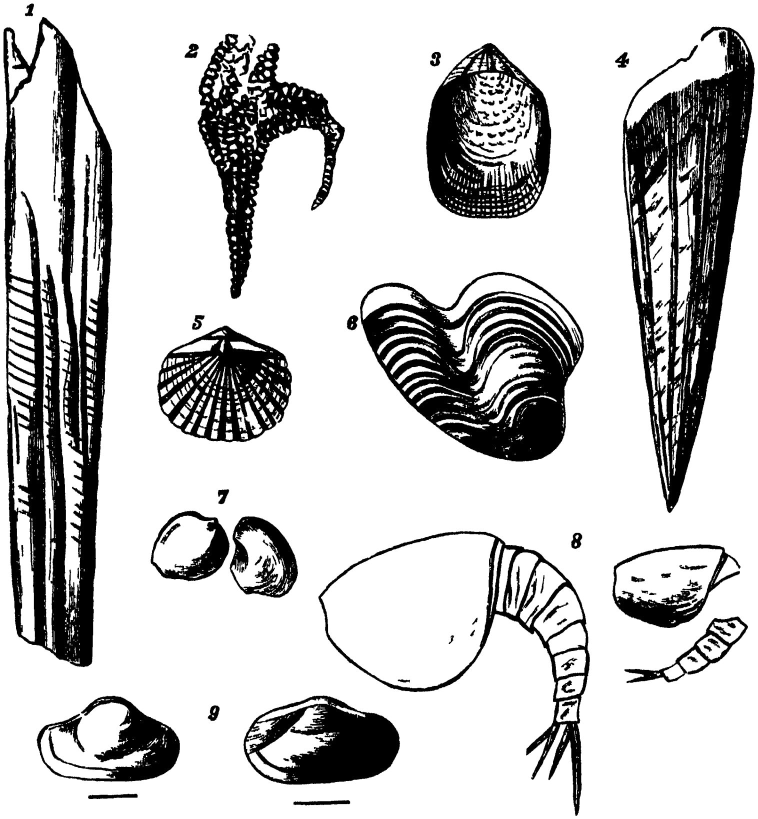

Fig. 339.—Group of Cambrian Fossils

1, Orthoceras sericeum, Salt., 2, Palæasterina ramseyensis, Hicks, 3, Lingulella Davisii, McCoy; 4, Conularia Homfrayi, Salt.; 5, Orthis Carausii, Salt; 6, Bellerophon arfonensis, Salt; 7, Palæarca Hopkinsoni, Hicks; 8, Hymenocaris vermicauda, Salt (and enlarged), 9, Ctenodonta cambrensis, Hicks (enlarged).

In striking contrast to the thoroughly Palæozoic and long extinct order of trilobites, the brachiopods appear in genera of the simple non-articulated group which are still familiar in the living world; but the more highly organised articulate division is also represented. *Lingula* and *Discina* (Fig. 338), which appear among these ancient rocks, have persisted with but little change, at least in external form, through the whole of geological time and are alive still. Other genera are *Lingulella* (Fig. 339), *Acrotreta*, *Obolella* (Fig. 338), *Kutorgina*, *Linnarssonia*, *Orthis* (Fig. 339), and *Orthisina*. Every class of the true mollusca had its representatives in the Cambrian seas. The lamellibranchs occurred in the genera *Ctenodonta* (Fig. 339), *Palæarca* (Fig. 339), *Davidia*, *Modiolopsis*, and *Fordilla*. The gasteropods were present in the heteropod genus *Bellerophon* (Fig. 339), so characteristic of Palæozoic time, also in *Scenella*, *Stenotheca*, *Platyceras*, and *Pleurotomaria*. The pteropods were represented by the genera *Hyolithes* or *Theca* (Fig. 338) *Hyolithellus*, *Salterella* and *Conularia* (Fig. 339), the cephalopods by *Orthoceras* (Fig. 339).

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[1] *Q. J. Geol. Soc.* xxviii. p. 174.

Taking palæontological characters as a guide in classification, and especially the distribution of the trilobites, geologists have grouped the Cambrian rocks in three divisions—the lower or Olenellus group, the middle or Paradoxidian, and the upper or Olenidian.

§ 2. Local Development.

Britain.[1]—The area in which the fullest development of the oldest known Palæozoic rocks has yet been found is undoubtedly the principality of Wales. The rocks are there of great thickness (12,000 feet or more), they have yielded a fauna which, though somewhat scanty, is sufficient for purposes of stratigraphical correlation, and they possess additional importance from the fact that they were the first strata of such antiquity to be worked out stratigraphically and palæontologically. As already stated, they were called Cambrian by Sedgwick, from their extensive development in North Wales (Cambria), where he originally studied them. Their true base is nowhere seen. Professor Hughes, Dr. Hicks, Professor Bonney and others believe that a conglomerate and grit generally mark the base of the Cambrian series.[2] According to Sir A. C. Ramsay, on the other hand, the base of the Cambrian series is either concealed by overlying formations or by the metamorphism which, in his opinion, has converted portions of the Cambrian series into various crystalline rocks. Both in Pembrokeshire and Carnarvonshire the lowest visible slates, shales, and sandstones are intercalated with and pass down into a volcanic series (felsites, diabases, and tuffs) the base of which has not been found. In certain localities, as in Anglesey, Cambrian strata are seen to lie unconformably on pre-Cambrian schists, and there not only the basement volcanic group but some of the lowest members of the fossiliferous series are wanting. There is then not only an unconformable junction, but an overlap.

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[1] See Sedgwick's Memoirs in *Quart. Journ. Geol. Soc.* vols. i. ii. iv. viii., and his 'Synopsis of the Classification of the British Palæozoic Rocks,' 4to, 1855; Murchison's 'Silurian System' and 'Siluria'; Salter's 'Cat. of Cambrian and Silurian Fossils,' with preface by Sedgwick, 1873; Ramsay's 'North Wales,' *Geological Survey Memoirs*, vol. iii.; and papers by Salter, Harkness, Hicks, Hughes, and others in the *Quart. Journ. Geol. Soc.* and *Geol. Mag.*, to some of which reference is made below. J. E. Marr, in his 'Classification of the Cambrian and Silurian Rocks,' gives a bibliography of the subject up to 1883.

[2] *Q. J. Geol. Soc.* xxxiv. p. 144; xl. (1884) p. 187. For references to the literature of the subject see the same Journal, xlvii. (1891) Ann. Address, p. 90 *seq.*

Starting from the volcanic group at the base the geologist can trace an upward succession through thousands of feet of grits and slates into the Silurian system. Considerable diversity of opinion has existed as to the line where the upper limit of the Cambrian division should be drawn. Murchison contended that this line should be placed below strata where a trilobitic and brachiopodous fauna begins, and that these strata cannot be separated from the overlying Silurian system. He therefore included as Cambrian only the barren grits and slates of Harlech, Llanberis, and the Longmynd. Sedgwick, on the other hand, insisted on carrying the line up to the base of the Upper Silurian rocks. He thus left these rocks as alone constituting the Silurian system, and massed all the Lower Silurian rocks in his Cambrian system. Murchison worked out the stratigraphical order of succession from above, chiefly by help of organic remains. He advanced from where the superposition of the rocks is clear and undoubted, and for the first time in the history of geology, ascertained that the "Transition-rocks" of the older geologists could be arranged into zones by means of characteristic fossils, as satisfactorily as the Secondary formations had been classified in a similar manner by William Smith. Year by year, as he found his Silurian types of life descend farther and farther into lower deposits, he pushed backward the limits of his Silurian system. In this he was supported by the general consent of geologists and palæontologists all over the world. Sedgwick, on the other hand, attacked the problem rather from the point of stratigraphy and geological structure. Though he had collected fossils from many of the rocks of which he had made out the true order of succession in North Wales, he allowed them to lie for years unexamined. Meanwhile Murchison had studied the prolongations of some of the same rocks into South Wales, and had obtained from them the copious suite of organic remains which characterised his Lower Silurian formations. Similar fossils were found abundantly on the continent of Europe and in America. Naturally the classification proposed by Murchison was generally adopted. As he included in his Silurian system the oldest rocks then known to contain a distinctive fauna of trilobites and brachiopods, the earliest fossiliferous rocks were everywhere classed as Silurian. The name Cambrian was regarded by geologists of other countries as the designation of a British series of more ancient deposits not characterised by peculiar organic remains, and therefore not capable of being elsewhere satisfactorily recognised. Barrande, investigating the most ancient fossiliferous rocks of Bohemia, distinguished by the name of the "Primordial Zone" a group of strata forming the lowest member of the Silurian system, and containing a peculiar and characteristic suite of trilobites. Murchison adopted the term, grouping under it the lowest dark slates which in Wales and the border English counties contained some of the same early forms of life.

Subsequent investigations, by the late Mr. Salter and Dr. Hicks, brought to light, from the Primordial rocks of Wales, a much more numerous fauna than they were supposed to possess, and one in some degree distinct from that in the undoubted Lower Silurian rocks. Thus the question of the proper base of the Silurian system was re-opened, and much controversy arose as to the respective limits and relative stratigraphical value of the formations to be included under the designations Cambrian and Silurian. No such marked break, either palæontological or stratigraphical, had been found as to afford a clear line of division between two distinct "systems." Those who followed Murchison contended that even if the line of division were drawn at the upper limits reached by the primordial fauna, the Cambrian could not be considered to be a system as well defined and important as the Silurian, but that it ought rather to be regarded as the lower member of one great system comprising the primordial, and the second and third faunas, so admirably worked out by Barrande in Bohemia. To this system they maintained that the name Silurian, in accordance with priority and justice, should be assigned. Unfortunately a disagreement, which was not settled during the lifetime of Sedgwick and Murchison, bequeathed a dispute in which personal feeling played a large part. And though the fires of controversy have died out, it cannot be said that the questions in debate have been left in a wholly satisfactory footing. For myself I repeat what I have said in previous editions of this text-book, that the most natural and logical classification is to group Barrande's three faunas as one system which in accordance with the laws of priority should be called Silurian. But as this arrangement has not been generally adopted in this country I retain the Cambrian in the position which has here been usually assigned to it.[1]

The Cambrian rocks of Britain vary widely in mineralogical composition, thickness, and area of exposure in the different districts where they rise to the surface. In North Wales, where they cover the widest extent of ground, they consist of purple, reddish-grey, green, and black slates, grits, sandstones, and conglomerates, with a volcanic group at the bottom, the whole attaining a thickness of probably more than 12,000 feet. In Western England this enormous mass of sedimentary material has dwindled down to a fourth or less, consisting at the base of quartzite and sandstone, and in the upper part of shales. In the East of Ireland, rocks assigned to the Cambrian system resemble on the whole the Welsh type. In the north-west of Scotland, on the other hand, the Cambrian strata, about 2000 feet thick, consist of quartzites below, graduating upwards into massive limestones. The following grouping of the British Cambrian rocks has been made:—

	Wales (ranging up to 12,000 feet or more).	Western England (about 3000 feet).	N.W. Scotland (2000 feet).
Upper or Olenus Zones.	Tremadoc Slates. Lingula Flags (*Lingulella*, *Olenus*, &c.)	Shineton Shales (*Dictyograptus* (*Dictynema*) *Olenus*, &c.)	A thick mass of limestone divisible into seven groups with *Archæocyathus*, *Maclurea*, *Ophileta*, *Murchisonia*, *Orthoceras*, and vast quantities of annelid castings.
Middle or Paradoxides Zones.	Menevian Group (*Paradoxides*).	Conglomerates and limestones (Comley) with *Paradoxides*, &c.	
Lower or Olenellus Zones.	Harlech and Llanberis group and basement volcanic rocks ("Pebidian" of Dr. Hicks, p. 710), bottom not seen.	Thin quartzite passing up into green flags, grits, shales, and sandstone (Comley Sandstone) containing *Olenellus*.	Shales with *Olenellus*, *Salterella*. Quartzites, with annelid burrows (p. 699).

LOWER.[2]—In South Pembrokeshire the lowest visible Cambrian rocks are of volcanic origin. They consist of fine tuffs, and silky schists with sheets of olivine-diabase and andesite, and intrusive quartz-porphyries.[1] It is this volcanic group which Dr. Hicks has proposed to class as a pre-Cambrian formation under the name of "Pebidian." In Carnarvonshire the Llanberis Slates, which form the lowest member of the Cambrian sedimentary series, are interleaved at their base with bands of volcanic tuffs and rest upon a mass of quartz-felsite which is the lowest rock visible in the district.[2]

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[1] After the first edition of this work was written, in which the future merging of Cambrian and Silurian into one great system was regarded as probable, M. Hébert thus expressed himself: "I adopt the opinion of M. Barrande, based as it was on such thorough and prolonged research, that there is one common character in his three first faunas which unites them into one great whole. To these faunas and the beds containing them I assign the name Silurian, because the Silurian fauna was the first to be determined; and, further, I am of opinion that the Cambrian group ought not to appear in our nomenclature as of equal rank with the Silurian group, of which it is merely a subdivision."—*Bull. Soc. Géol. France* (3) xi. (1882) p. 34. F. Schmidt, also, would prefer to regard the Cambrian as only part of one system extending up to the overlying unconformable Devonian rocks. *Q. J. Geol. Soc.* xxxviii. (1882) p. 515. My friend Prof. De Lapparent has followed the same principle, making the Silurian system range from the base of the primordial zone to the base of the Devonian rocks. 'Traité de Géologie,' 3rd Edit. (1893). See also *postea*, p. 737.

[2] The chief authority on the fossils of the Lower Cambrian rocks is the monograph by C. D. Walcott, "The Fauna of the Lower Cambrian or *Olenellus* Zone," published in the *10th Ann. Rep. U.S. Geol. Surv.* (1890). This work contains figures and descriptions of this the oldest known distinct assemblage of organisms, and gives a bibliography of the subject up to the year of publication. Some of the other more important memoirs will be cited in subsequent pages.

The Olenellus zone which is the characteristic feature of the lower Cambrian group has not yet been certainly established in Wales.[3] It was first detected in the British Isles by Prof. Lapworth, who in 1885 found fragments of *Olenellus* on the flanks of Caer Caradoc in Shropshire, associated with *Kutorgina cingulata*, *Linnarssonia sagittalis*, *Hyolithellus* and *Ellipsocephalus*.[4] It has been found by the officers of the Geological Survey in the west of Ross-shire, where the following lower Cambrian strata may be traced in a narrow strip of country for a distance of more than 100 miles:[5]—

Base of Durness limestones with *Salterella*.

Band of quartzite and grit (Serpulite grit) with abundant *Salterella Maccullochii* and occasionally thin shales with *Olenellus*.

Calcareous and dolomitic shales ("Fucoid beds") with numerous worm-casts usually flattened and resembling fucoidal impressions. *Olenellus* occurs in bands of dark blue shale.

Quartzites, in two divisions, the upper crowded with worm-burrows, the lower becoming pebbly at the base and resting unconformably on pre-Cambrian rocks (Torridonian or Lewisian).

MIDDLE.—This group appears to be most fully developed in South Wales, where it was first studied by Dr. Hicks, and found to yield a number of characteristic fossils. He has divided it into two groups, the Solva below and Menevian above. From the lower group a number of trilobites, including the typical genus *Paradoxides*, have been obtained, also *Plutonia*, *Microdiscus*, *Agnostus*, *Conocoryphe*. There occur likewise annelides (*Arenicolites*), brachiopods (*Discina*, *Lingulella*), pteropods (*Theca*), and a sponge (*Protospongia*).

The name Menevian was proposed by J. W. Salter and Dr. Hicks for a series of sandstones and shales, with dark-blue slates, flags, and grey grits, which are seen near St. David's (Menevia), where they attain a depth of about 600 feet. They pass conformably into the Lower, and also into the Upper group. They have yielded upwards of 50 species of fossils, among which trilobites are specially prominent. *Paradoxides* is the typical genus, while *Agnostus* and *Conocoryphe* are of frequent occurrence. Sponges (*Protospongia*) and annelide-tracks likewise occur. The mollusca are represented by brachiopods of the genera *Discina*, *Lingulella*, *Obolella*, and *Orthis*; and by pteropods (*Cyrtotheca*, *Theca*). An entomostracan (*Entomis*) and cystidean (*Protocystites*) have also been met with.

UPPER.—This highest section of the system has long been divided in Wales into two well-marked groups of strata, the Lingula Flags below and the Tremadoc Slates above. As already stated, its characteristic palæontological feature is the prevalence of trilobites of the genus *Olenus*.

Lingula Flags.—These strata, consisting of bluish and black slates and flags, with bands of grey flags and sandstones, attain in some parts of Wales a thickness of more than 5000 feet. They received their name from the vast numbers of a lingula (*Lingulella Davisii*) in some of their layers. They rest conformably upon, and pass down into, the Menevian group below them, and likewise graduate into the Tremadoc group above. They are distinguished by a characteristic suite of organic remains. The trilobites include the genera *Olenus*, *Agnostus*, *Anopolenus*, *Conocoryphe*, *Dikelocephalus*, *Erinnys*, and *Paradoxides*. Early forms of phyllopods (*Hymenocaris*) and heteropods (*Bellerophon*) occur in these strata. The brachiopods include species of *Lingulella* (*L. Davisii*), *Discina*, *Obolella*, *Kutorgina*, and *Orthis*. The pteropods are represented by species of *Theca*. Several annelides (*Cruziana*) and polyzoa (*Fenestella*) likewise occur.

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[1] *Quart. Journ. Geol. Soc.* xxxix. (1883) p. 294, C. Lloyd Morgan, *op. cit.* xlvi. (1890) p. 241.

[2] *Op. cit.* xlvii. (1891). Presidential Address, p. 90, and authorities there cited.

[3] Dr. Hicks believes that it exists there, *Geol. Mag.* 1892, p. 21.

[4] Lapworth, *Geol. Mag.* 1888, p. 484; 1891, p. 529.

[5] *Brit. Assoc. Rep.* 1891, p. 633. Peach and Horne, *Quart. Journ. Geol. Soc.* xlviii. (1892) p. 227.

A subdivision of the Lingula Flags into three sub-groups has been proposed by Mr. T. Belt, in descending order as follows :[1]—

3. Dolgelly slates, about 600 feet, well seen at Dolgelly, consist of soft and hard blue slates and contain *Protospongia*, *Lingulella*, *Orthis lenticularis*, *Olenus scarabæoides*, *O. spinulosus*, *Agnostus trisectus*, *Conocoryphe abdita*.
2. Ffestiniog flags, about 2000 feet, well seen at Ffestiniog, consist of hard sandy micaceous flagstones, and have yielded *Lingulella Davisii*, *Olenus micrurus*, *Hymenocaris vermicauda*, *Bellerophon cambrensis*.
1. Maentwrog flags and slates, about 2500 feet, best seen at Maentwrog in Merionethshire, consist of grey and yellow flagstones, and grey, blue, and black slates, and contain among their somewhat scanty fossils, *Olenus cataractes*, *O. gibbosus*, *Agnostus princeps* (*pisiformis*), *A. nodosus*.

Tremadoc Slates.—This name was given by Sedgwick to a group of dark grey slates, about 1000 feet thick, found near Tremadoc in Carnarvonshire, and traceable thence to Dolgelly in Merionethshire. and reappearing beyond the eastern side of Wales at the Wrekin, in Shropshire.[2] Their importance as a geological formation was not recognised until the discovery in them of a remarkably abundant and varied fauna, which now numbers more than 80 species, including early forms of crinoids, star-fishes, lamellibranchs, and cephalopods. The trilobites embrace some genera (*Olenus*, *Agnostus*, *Conocoryphe*, *Dikelocephalus*, &c.) found in the Lingula flags, but include also new forms, (*Angelina*, *Asaphus*, *Cheirurus*, *Nescuretus*, *Niobe*, *Ogygia*, *Psilocephalus*). The phyllopods are represented by *Ceratiocaris* and *Lingulocaris*. The same genera, and in some cases species, of brachiopods appear which occur in the Lingula flags, *Orthis lenticularis* and *Lingulella Davisii* being common forms. Dr. Hicks has described 12 species of lamellibranchs from the Tremadoc rocks of Ramsey Island and St. David's, belonging to the genera *Ctenodonta*, *Palæarca*, *Glyptarca*, *Davidia*, *Modiolopsis*. The cephalopods are represented by *Orthoceras sericeum* and *Cyrtoceras præcor* ; the pteropods by *Theca Davidii*, *T. operculata*, and *Conularia Homfrayi* ; the echinoderms by a beautiful star-fish (*Palæasterina ramseyensis*) and by a crinoid (*Dendrocrinus cambrensis*).[3] Careful analysis of the fossils suggests a separation of the Tremadoc sub-group into two divisions. The most characteristic forms of the lower division are *Niobe Homfrayi*, *N. menapiensis*, *Psilocephalus innotatus*, *Angelina Sedgwickii*, *Asaphus affinis*, and more particularly *Dictyograptus flabelliformis* (*Dictyonema sociale*), which is a characteristic fossil of the uppermost Cambrian rocks in Scandinavia and Russia. The upper division contains *Asaphus Homfrayi*, *Conocoryphe depressa*, and other fossils having a general lower Silurian facies.

It is at the top of the Tremadoc strata that the upper limit of the Cambrian or Primordial formations is now drawn in Britain. The late Sir A. C. Ramsay was of opinion that though no visible unconformability could be seen at this horizon, nevertheless there was evidence on a large scale of the transgressive superposition of the Arenig rocks upon the Tremadoc Slates and Lingula flags below them.[4]

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[1] *Geol. Mag.* (1867) p. 538.

[2] Callaway, *Q. J. Geol. Soc.* xxxiii. (1877) p. 652. Lapworth, *op. cit.* (1888) p. 485, (1891) p. 533.

[3] Hicks, *Quart. Journ. Geol. Soc.* xxix. p. 39.

[4] *Mem. Geol. Surv.* vol. iii. 'Geology of North Wales,' p. 250.

There appears to be more satisfactory proof of a distinct palæontological break at this stage of the geological record in Britain, or at least between the lower and upper part of the Tremadoc sub-group. Up to the present time rather more than seventy species of fossils have been chronicled from the Tremadoc Slates. Of these so far as we know at present only eighteen pass up into the Arenig group above. As these surviving species possess a special interest, in that they connect by a link of continued organic life two great geological periods of such remote antiquity, they are here named—*Arenicolites linearis*, *Asaphus affinis*, *A. Homfrayi*, *Calymene Blumenbachii*, *Cheirurus Frederici*, *Ogygia peltata*, *O. scutatrix*, *O. Selwynii*, *Lingula petalon*, *L. Davisii*, *L. lepis*, *Orthis Carausii*, *O. lenticularis*, *O. Menapiæ*, *Conularia Homfrayi*, *Theca simplex*, *Bellerophon multistriatus*, *Orthoceras sericeum*.[1]

In the north-west of Scotland, the discovery of the *Olenellus*-zone, already referred to, has given a definite geological horizon from which to work out the stratigraphical succession above and below. It has conclusively proved that the thick mass of Torridon sandstone, formerly classed as Cambrian, must now be relegated to the pre-Cambrian series (*ante*, p. 699). Above the quartzite and shales which include the *Olenellus*-zone there lies a series of limestones which attain an aggregate thickness of about 1500 feet. Their original upper limit, however, cannot now be ascertained, for it has been concealed by the great dislocations which have so complicated the structure of that region (see Figs. 311, 334). We cannot tell what additional thickness of limestone may have been accumulated in the north-west at the time when only mud, silt, and sand, were deposited over the southern parts of the British area, nor by what kind of sediment the limestones were succeeded. The limestones are most fully developed around Durness in the extreme north-west of Sutherland, where they have yielded a large number of fossils. The facies of these fossils, however, is so peculiar that it has not yet been possible by their means to correlate the rocks containing them with the Cambrian formations of Wales. The limestones are so crowded with worm-casts that, as Mr. Peach has pointed out, nearly every particle of their mass must have passed through the intestines of worms. Hence they are obviously of detrital origin, and were probably formed in chief part by small pelagic animals. Only one coral has been found in them. The most abundant fossils are chambered shells (*Orthoceratites, Lituites, Nautilus*); next in number are gasteropods (chiefly *Maclurea* and *Pleurotomaria*), while the lamellibranchs and brachiopods come last. The bivalves have their valves still united, and the lamellibranchs retain the positions in which they lived. "All the specimens show that every open space into which the calcareous mud could gain access, and the worms could crawl, is traversed by worm-casts. In the case of the *Orthoceratites*, they seem to have lain long enough uncovered by sediment to allow the septa to be dissolved away from the siphuncles which they held in place; many of these siphuncles are now found isolated." Sponges of the genus *Calathium* are scattered through the calcareous sediment, and likewise the doubtful but characteristic Cambrian forms, known as *Archæocyathus* which, once referred to the sponges, are now thought to be more probably allied to the madrepores. The general assemblage of fossils, as was originally pointed out by Salter, is of a distinctly North American type, and does not resemble that found in the slates, flags, and grits of Wales. The conditions of deposit must have been so entirely different that a great contrast in the organisms of the two areas of sedimentation could not but occur. Whether or not the contrast further arose from some geographical cause, such as a land-barrier, that completely separated the areas remains uncertain. The Durness limestones, as regards their fossil contents and lithological character, may be compared with the Potsdam sandstone and Calciferous group of the United States and Canada. They represent the Middle and Upper Cambrian, possibly part of the Lower Silurian formations.[2]

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[1] This list is compiled from Mr. Etheridge's "Fossils of the British Islands," vol. i. (1888).

[2] B. N. Peach, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 407.

In the south-east of Ireland masses of purplish, red, and green shales, slates, grits, quartzites, and schists occupy a considerable area and attain a depth of apparently several thousand feet without revealing their base, though in Wexford they may possibly rest on pre-Cambrian rocks. Their top is covered by unconformable formations (Lower Silurian and Lower Carboniferous). They have yielded *Oldhamia*, also numerous burrows and trails of annelides (*Histioderma hibernicum*, *Arenicolites didymus*, *A. sparsus*, *Haughtonia pœcila*). In the absence of fossil evidence it is impossible to bring these strata into correlation with those of Wales. Some portions of them have been considerably metamorphosed. On the Howth coast they appear as slates, schists, and quartzites, and include there some remarkable breccias, as well as single blocks of stone scattered through the slates.[1]

Continental Europe.—According to the classification adopted by M. Barrande, the fauna of the older Palæozoic rocks of Europe suggest an early division of the area of this continent into two regions or provinces,—a northern province, embracing the British Islands, and extending through North Germany into Scandinavia and Russia, and a central-European province, including Bohemia, France, Spain, Portugal, and Sardinia.

Passing from the British type of the Cambrian deposits, we encounter nowhere in the northern part of the continent so vast a depth of stratified deposits ; on the contrary, one of the most singular contrasts in Palæozoic geology is that presented by the development of these formations in Wales, and in the north of Europe. The enormous masses of sediment, thousands of feet thick, and with such uniformity of lithological character, which record the oldest Palæozoic ages in Wales, are represented in the basin of the Baltic by only a few hundred feet of sediments, which show strongly separated lithological subdivisions. Again, while the English and Welsh rocks have been much disturbed and even metamorphosed, those in the eastern part of the Baltic basin remain over wide tracts hardly altered from their original condition of level sheets of sand and clay.

In Scandinavia the Cambrian system lies with a strong unconformability on pre-Cambrian rocks. The so-called "Primordial zone" of this region appears to be everywhere characterised by uniformity of lithological composition as well as of fossil contents, consisting mainly of black shales with concretions or thin seams of fetid limestone. In Scania the following grouping of the Cambrian system has been made, the whole thickness of strata being about 400 Norwegian feet (120 metres).

3. Olenus group. About 200 feet of bituminous fissile alum-shales, with nodules and layers of fetid limestone. The following zones in descending order are noted by S. A. Tullberg—(*k*) zone with *Acerocare ecorne*, (*i*) *Dictyonema flabelliforme*, (*h*) *Cyclognathus mycropygus*, (*g*) *Peltura scarabæoides*, (*f*) *Eurycare camuricorne*, (*e*) *Parabolina spinulosa*, (*d*) *Ceratopyge* sp., (*c*) *Olenus* (the special zone of this genus of which it has many species), (*b*) *Leperditia* sp., (*a*) *Agnostus pisiformis*.

   Professor Brogger has abbreviated this subdivision by making two chief zones, a higher with *Peltura*, *Cyclognathus*, &c., and a lower with *Olenus* (in the strict sense) *Parabolina*, *Eurycare*, &c.

2. Paradoxides group. About 160 feet of sandy shales, alum shales, with three bands of limestone, the lowest (1½ feet), known as the "Fragmentenkalk," the middle as the "Exsulanskalk," and the highest (2 to 3 feet) the "Andrarumskalk." Mr. Tullberg divides the group into the following zones in descending order, (*m*) *Agnostus lævigatus*, (*l*) *Paradoxides Forchhammeri*. (This is the horizon of the Andrarum limestone, which contains an abundant fauna, including many species of *Agnostus* and other trilobites.) (*k*) *Agnostus Lundgreni*, (*i*) *Paradoxides Davidis*, (*h*) *Conocoryphe æqualis*, (*g*) *Agnostus rex*, (*f*) *Agnostus intermedius*, (*e*) *Microdiscus scanicus*, (*d*) *Conocoryphe exsulans*, (*c*) *Agnostus atavus*, (*b*) "Fragmentenkalk" with *Paradoxides ölandicus*, (*a*) Black alum-shale with *Lingulella*, *Acrotreta*, *Obolella*, &c.

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[1] *Quart. Journ. Geol. Soc.* xlvii. (1891). Presidential Address, p. 104.

Professor Brogger recognises two chief bands the higher marked by *Paradoxides Forchhammeri*, the lower by *P. ölandicus P. Tessini, P. Davidis*, &c.

1. Olenellus group, consisting of two thin bands of strata, (*b*) Phosphate limestone and sandy shale with *Lingulella, Acrothele*, &c., (*a*) Sandy shales passing into sandstone (greywacke-shale) with *Olenellus Kjerulfi, Ellipsocephalus Nordenskioldi, Arionellus primævus, Hyolithes*, &c.[1]

In the Christiania district the lowest stage of the Cambrian series is 90 Norwegian feet thick and is composed of conglomerates, sandstones, and dark shales with limestone. It includes the *Olenellus* zone and that of *Paradoxides*. It is surmounted by an upper stage (150 feet) composed of black slates (alum-shales) and fetid limestone, with *Olenus*, &c. This upper or Olenus stage has been grouped by Brögger into the following five members in ascending order: (*a*) Zone of *Agnostus pisiformis, Olenus truncatus*; (*b*) *Parabolina spinulosa* beds; (*c*) *Eurycare latum* beds; (*d*) shales with bands and nodules of limestone, *Peltura scarabæoides*; (*e*) *Dictyograptus* shales with *Dictyograptus* (*Dictyonema*) *flabelliformis*.[2]

Though the Scandinavian Cambrian series is so much thinner than that of Wales, it contains the three distinctive life-platforms recognisable in Britain, and appears thus to be a full palæontological and homotaxial equivalent of the much fuller development of sedimentary material in Britain. The Cambrian type of Southern Sweden undergoes considerable modification as it passes eastwards, into the Baltic provinces of Russia. The black shales so characteristic in Scandinavia thin away, and the distinctive paradoxidian and olenidian divisions disappear. A group of strata, traceable from the S.E. of Lake Ladoga for a distance of about 330 miles to near Baltischport on the Gulf of Finland, with a visible thickness of not more than 100 feet (but pierced to a depth of 600 feet more in artesian wells) consists of three subdivisions; (*a*) Blue clay composed of a lower set of iron-sandstones (300 feet) resting on granite and an upper blue clay (300 feet), formerly noted only for some obscure fossils (*Platysolenites*, Pander, probably fragments of cystideans) but now known to include the *Olenellus*-zone; (*b*) Ungulite grit (50 to 60 feet) containing *Obolus Apollinis* (*Ungula*, Eichw.) *Schmidtia celata*, &c.; (*c*) *Dictyonema*-shales (about 20 feet) with *Dictyograptus* (*Dictyonema*) *flabelliformis*.[3] The recent researches of Schmidt have clearly shown the relations between these soft and seemingly not very old deposits and the Cambrian system of the rest of Europe. The lower sandstone, blue clay and a fucoidal sandstone lying immediately above the latter form an unequivocally Lower Cambrian group, for they have yielded *Olenellus Mickwitzi, Scenella discinoides, Mickwitzia monilifera, Obolella, Discina, Volborthella* (doubtfully referred to the orthoceratites), *Platysolenites* and *Medusites*. Schmidt points out that a complete break occurs between the top of the fucoid sandstone and the base of the

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[1] S. A. Tullberg, *Afhand. Sveriges Geol. Undersökn.* ser. C. No. 50 (1882). W. C. Brogger, *Geol. För. Stockholm Förhandl.* No. 101, vol. viii. (1886) p. 196.

[2] For Scandinavian Cambrian rocks see Angelin, 'Palæontologica Suecica,' 1851-54. Kjerulf, 'Geologie des Sud. und Mittl. Norwegen,' 1880. Dahll, *Vidensk. Selsk. Förhandl.* 1867. Nathorst, *Kongl. Vet. Akad. Förhandl.* 1869, p. 64, and 'Sveriges Geologi.' Torell, *Acta Univers. Lund*, 1870, p. 14, *Kongl. Vet. Akad. Forhandl.* 1871, No. 6. Linnarsson, *Svensk. Vet. Akad. Handl.* 1876, iii. No. 12: 'Om Agnostus-Arterna,' &c., *Sveriges Geol. Undersökn.* ser. C. No. 42, 1880. 'De undre Paradoxides lageren vid Andrarum,' *op. cit.* ser. C. No. 54, 1883; *Geol. Mag.* 1869, p. 393; 1876, p. 145. Tullberg, 'Skanes Graptoliter,' *Sveriges Geol. Undersökn.* ser. C. Nos. 50, 55 (1882, 3); *Z. Deutsch. Geol. Ges.* xxxv. (1883), p. 223. W. C. Brögger, *Nyt. Mag.* 1876; *Geol. Fören. Stockholm Förhandl.* 1875-1876, 1886, p. 18. 'Die Silurischen Etagen 2 und 3 im Kristiania Gebiet, 1882.' Lundgren in text to Angelin's Geol. Map of Sweden, *N. Jahrb.* 1878. Lapworth, *Geol. Mag.* 1881, p. 260; 1888, p. 484. Marr, *Q. J. Geol. Soc.* xxxviii. (1882) p. 313. 'Classification of the Cambrian and Silurian Rocks,' 1883, pp. 72-100.

[3] F. Schmidt, *Quart. Journ. Geol. Soc.* xxxviii. (1882) p. 516.

Ungulite sandstone, and that this hiatus represents the Paradoxidian and Olenidian groups, while the Dictyonema-shales form the characteristic uppermost zone of the system.[1]

In Central Europe, Cambrian rocks appear from under later accumulations in Belgium and the north of France, Spain, Bohemia, and the Thuringer Wald.[2] The most important in France and Belgium is that of the Ardennes,[3] where the principal rocks are grit, sandstone, slates, and schistose quartzites or quartz-schists (quartzo-phyllades of Dumont), with bands of whet-slate, quartz-porphyry, diabase, diorite, and porphyroid. According to Dumont these rocks, comprehended in his 'Terrain Ardennais,' can be grouped into three great subdivisions—1st and lowest the "Système Devillien," pale and greenish quartzites with shales or phyllades, containing *Oldhamia radiata* and annelide tracks (*Nereites*); 2nd, the "Système Revinien," phyllades and black pyritous quartzites from which *Dictyograptus flabelliformis* (*Dictyonema sociale*), and worm-burrows have been obtained; 3rd, the "Système Salmien," consisting mainly of quartzose and schistose strata or quartzo-phyllades, and yielding *Dictyograptus flabelliformis*, *Chondrites antiquus* and *Lingula*. The Devillian and Revinian divisions are united by Gosselet into one series composed of (*a*) Violet slates of Fumay; (*b*) Black pyritous shales of Revin; (*c*) magnetite slates of Deville; (*d*) Black pyritous shales of Bogny. These rocks have been greatly disturbed. They are covered unconformably by Devonian and later formations. In the north-west of France extending through the old provinces of Brittany, the west of Normandy and the north of Poitou, a great isolated mass of ancient rocks rises out of the plains of Secondary formations, and the pre-Cambrian rocks already referred to are there succeeded, with a more or less distinct unconformability, by a thick series of sedimentary groups which are now considered to be of Cambrian age. In western Brittany the pre-Cambrian green silky schists known as the "Phyllades de Douarnenez," which are believed to be about 3000 metres thick, are followed, perhaps unconformably, by purple conglomerates, sometimes 530 metres thick, and passing up into red shales which have a vertical depth of 2500 metres, and are surmounted by the Grès Armoricain or bottom of the Silurian system. In these strata *Scolithus* and *Tigillites* occur, but recognisable fossils are extremely rare, and no trace has yet been found here of the more typical Cambrian forms. In the basin of Rennes considerable bands of limestone, sometimes magnesian, together with quartzites, conglomerates, and greywackes occur in the Cambrian series. In the region of the Sarthe basement conglomerates are followed by grey shales with thick bands of siliceous and magnesian limestone, above which lies a series of sandy rocks containing *Lingula crumena* and passing under the Grès Armoricain.[4] In southern France from the Cambrian rocks which flank the isolated pre-Cambrian axis of upper Languedoc the most satisfactory fossil evidence has recently been obtained, showing the existence there of both the Paradoxidian (*Paradoxides*, *Conocoryphe*) and Olenidian divisions of the Cambrian system.[1] Among the French Pyrenees, narrow strips and patches of strata have been detected which, lying below fossiliferous Lower Silurian rocks, are believed to be Cambrian.[2]

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[1] *Mém. Acad. Imp. Sci. St. Pétersbourg*, xxxvi. (1889) No. 2.

[2] The student will find a useful compendium on the correlation of the Cambrian and Silurian rocks of western Europe by S. Tornquist in *Geolog. Foren. Stockholm Forhandl.* xi. (1889) p. 299.

[3] Dumont, 'Mémoires sur les Terrains Ardennais et Rhénan,' 1847-48. Dewalque, 'Prodrome d'une Description Géol. de la Belgique,' 1868. Mourlon, 'Géologie de la Belgique,' 1880. Gosselet, 'Esquisse Géol. du Nord de la France, &c.,' 1880, and his great Monograph, 'L'Ardenne,' *Mém. Carte Géol. detaill.* 4to, 1888.

[4] The (pre-Cambrian) phyllades of Brittany and the (Cambrian) purple conglomerates and red shales which succeed them were exhaustively treated by Hébert, *Bull. Soc. Géol. France*, (3) xiv. (1886) p. 713. See also, Tromelin et Lebesconte, *Bull. Soc. Géol. France*, iv. (1876) p. 583; Tromelin, *Assoc. Française* (1879), p. 493, Lebesconte, *Bull. Soc. Géol. France* (3) x. p. 55, xix. (1891) p. 15, Guillier, *op. cit.* (3) ix. p. 374; Barrois, *op. cit.* v. (1877) p. 266, *Carte Géol. France*, Redon sheet.

In various parts of Spain, indications of the presence of Cambrian rocks are furnished by Primordial fossils. In the province of Seville the highest beds have yielded *Archæocyathus*, and in the province of Ciudad-Reale, Primordial trilobites (*Ellipsocephalus*). But it is in the Asturias that the most abundantly fossiliferous rocks of this age occur. They are grouped by Barrois into (*a*) Slates of Rivadeo, blue phyllades and green slates and quartzites, in all about 3000 metres, and (*b*) Paradoxides beds of La Vega (50 to 100 metres) composed of limestones, slates, iron-ores, and thick beds of green quartzite. In the upper part of (*b*) a rich Primordial fauna occurs, comprising a cystidean (*Trochocystites bohemicus*) and trilobites of the genera *Paradoxides*, 2 species, *Conocoryphe* (*Conocephalites*), 3 species, and *Arionellus*, 1 species.[3]

In the Thuringer Wald certain phyllites, clay-slates, quartzites, &c., passing up into strata containing Silurian fossils are referred to the Cambrian system. The quartzites have yielded some indistinct fossils referred to *Davidia* and *Lingula*.[4] But it is in Bohemia that the central European type of the Cambrian system is best developed. The classic researches of Barrande have given to the oldest fossiliferous rocks of that country an extraordinary interest. At the base of the Bohemian geological formations lie the slates which Barrande placed as his Étage A (Przibram schists), and which are no doubt pre-Cambrian. They are overlain by vast masses of conglomerates, quartzites, slates, and igneous rocks (Étage B), which have been more or less metamorphosed, and are singularly barren of organic remains, though some of them have yielded traces of annelides (*Arenicolites*). They pass up into certain grey and green fissile shales, in which the earliest well-marked fossils occur. The organic contents of this Étage C or Primordial zone (300 to 400 metres thick) form what Barrande termed his Primordial fauna, which yielded him 40 or more species, of which 27 were trilobites, belonging to the characteristic Cambrian genera—*Paradoxides* (12), *Agnostus* (5), *Conocoryphe* (4), *Ellipsocephalus* (2), *Hydrocephalus* (2), *Arionellus* (1), *Sao* (1). Not one of these genera, save *Agnostus* (of which four species appear in the second fauna), were found by Barrande higher than his Primordial Zone. Among other organisms in this Primordial fauna, the brachiopods are represented by species of *Orthis* and *Orbicula*, the pteropods by *Theca*, and the echinoderms by cystideans. It is worthy of note that the fossil contents of the zone on the opposite sides of the little Bohemian basin were found by the same great pioneer to be not quite the same, only eight species of trilobites being common to both belts, while no fewer than 27 species were detected by him only on one or other side. The Olenidian trilobites which characterise the upper Cambrian group were not observed by him in Bohemia.[5] More recent researches have modified some of the stratigraphical details of his work, the geological structure of the country having been found to be much less simple than he supposed. But the fundamental grouping which he established remains much as he left it. A portion of his Stage B, the whole of his Primordial zone, (Stage C), and a part of the base of his Stage D (Lower Silurian), have been grouped together by Dr. Katzer in four members as the Cambrian development in Central Bohemia thus: (*a*) Basement conglomerates, (*b*) Paradoxides shales, (*c*) Quartz-greywacke group, (*d*) Diabase and red iron-ore group.[1] The Olenellus-zone has not been noticed.

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[1] J. Bergeron, *Bull. Soc. Géol. France*, xvi. (1888) p. 282, 'Étude géologique du massif ancien au sud du Plateau central,' 1889.

[2] J. Caralp, 'Études géol. sur les hauts massifs des Pyrénées centrales,' 1888, p. 452. E. Jacquot, *Bull. Soc. Géol. France*, 1890, p. 640.

[3] Barrande, *Bull. Soc. Géol. France* (2) xvi. p. 543. Macpherson, *Neues Jahrb.* 1879, p. 930. Barrois, *Mém. Soc. Géol. Nord*, ii. (1882) p. 168.

[4] H. Loretz, *Jahrb. Preuss. Geol. Landesanst.* 1881, p. 175. Marr, *Geol. Mag.* 1889, p. 411.

[5] See his colossal work, 'Système Silurien de la Bohème,' published in successive parts and volumes from 1852 up to his death in 1883; also Marr, *Quart. Journ. Geol. Soc.* xxxvi. (1880).

In Sardinia a characteristic assemblage of Cambrian fossils has been described by Prof. G. Meneghini, comprising three species of *Paradoxides*, six of *Conocephalites*, five of *Anomocare*, five of *Olenus*, as well as other forms.[2]

North America.—During the last decade a large amount of attention has been paid by the geologists of the United States and of Canada to the study of stratigraphy and fossil contents of the Cambrian rocks of North America, and the result of their labours has been to show that, whether as regards extent and thickness of strata, or variety and abundance of organic remains, these rocks surpass in importance the corresponding European series. The European types of sedimentation are replaced by a varied assemblage of materials, among which limestone plays a large part; and this change, as might be expected, is accompanied by a remarkable contrast in the general facies of the fossils. Nevertheless, the leading type-genera of Europe have been found in their usual sequence, so that it has been possible to subdivide the American Cambrian system into three groups which can be broadly correlated with the threefold arrangement adopted in Europe.

From the straits of Belle Isle the Cambrian formations of North America run through Newfoundland and Nova Scotia into New Brunswick. From the eastern coast of Gaspé they stretch along the right bank of the St. Lawrence to Lake Ontario. In several approximately parallel bands they range through the north-eastern states of the Union, spreading out more widely in the north of New York State, and in Vermont and Eastern Massachusetts. They rise along the Appalachian ridge, striking through Pennsylvania, Maryland, Virginia, Tennessee, and Georgia, down into Alabama, to a distance in the eastern part of the continent of about 2000 miles. In the heart of the continent, again, they rise to the surface, and flanking the vast pre-Cambrian region of the north, extend over a wide area between Lake Superior and the valley of the Mississippi in the States of Michigan, Wisconsin, and Minnesota. An isolated tract of them is found in Missouri, and another in Texas. The great terrestrial movements which ridged up the Rocky Mountains and their offshoots have brought the Cambrian rocks once more to the surface from under the vast pile of younger formations beneath which, during a large part of geological time, they lay buried. Hence along the axes of these elevations of the terrestrial crust they can be traced in many lines of outcrop from Arizona northwards through Utah, Colorado, Nevada, Wyoming, Dakota, and Montana, whence they strike far northward into the Dominion of Canada.

In thickness and lithological character the Cambrian rocks of North America exhibit considerable variation as they are traced across the continent, and these changes afford interesting evidence of the geographical conditions and geological revolutions of the region in the early ages of Palæozoic time.[3] In Newfoundland, where the three groups of the system have been recognised, the total depth of strata measured by A. Murray was about 6000 feet, of which the Lower division forms only about 200 feet. In Western

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[1] F. Katzer, 'Das altere Palæozoicum in Mittelbohmen,' Prague, 1888; 'Geologie von Bohmen,' Prague, 1892, p. 804.

[2] *Memorie per serv. alla descriz. della Cart. Geol. d'Italia*, III. part 2 (1888).

[3] Among writers on the Cambrian palæontology of North America a high place must be assigned to James Hall, E. Billings, C. D. Walcott, and G. F. Mathew. Mr. Walcott has devoted himself to the subject with untiring enthusiasm and much skill. His most important memoirs will be found in the Bulletins of the U.S. Geological Survey, Nos. 10 (1884), 30 (1886), 81 (1891), and in the 10th and 12th Annual Reports (1890). He gives a full bibliography. Of great importance also are the memoirs on the Cambrian rocks and fossils of Canada, by Mr. Mathew, published in the *Trans. Roy. Soc. Canada*, from the first volume (1882) onwards.

Vermont and Eastern New York the total depth of the system seems to be about 7000 feet; and of this great mass of sedimentary material the lower division may occupy perhaps as much as 5000 feet.[1] Over the central parts of the continent west of the line of the Mississippi the thickness diminishes to 1000 feet or less; but again to the west of the Rocky Mountains it increases to 7000 feet or more in Nevada, while in British Columbia it rises to 10,000 feet.

In the north-eastern regions the sediments were chiefly muddy, and are now represented by thick masses of shale with a little sandstone and limestone. The limestones increase in number and thickness southwards in Vermont, where a considerable mass of calcareous material lies in the lower group below several thousand feet of shale. Still further south the lower group consists largely of sandstones, which are followed by sandy, dolomitic, and purely calcareous limestones. In Nevada, where a thickness of 7700 feet has been assigned to the Cambrian system, the limestones are 4250 feet in aggregate thickness.[2]

It will be seen, therefore, that the nearest European parallel to the combination of thick arenaceous with thick calcareous accumulations, which distinguishes the Cambrian system of North America, is to be found in the north-west of Scotland. In this connection it is interesting to note that the general facies of the Scottish Cambrian fossils, so distinct from that of the rocks of Wales and the rest of Europe, and so much more akin to that of the United States and Canada, is accompanied by a markedly North American type of sedimentary material.

The following table gives the latest classification of the Cambrian system of North America:[3]—

Upper or Potsdam (Olenus and Dikelocephalus fauna).	Sandstones of N. and E. sides of Adirondack Mountains of New York and adjacent parts of Canada. On the same horizon lie the limestones S. of Adirondacks and Dutchess County, New York; and the shales of Tennessee, Georgia, and Alabama. In the west come the sandstones of the Upper Mississippi Valley, S. Dakota, Wyoming, Montana, and Colorado, the sandstones and calcareous beds of N. Arizona, and the limestones and shales of Nevada. In the far north-east are the black shales at the top of the New Brunswick and Cape Breton Island sections, and the shales and sandstones of Conception Bay, Newfoundland (Belle Isle).
Middle or Acadian (Paradoxides fauna).	Shales and slates of Eastern Massachusetts (Braintree), New Brunswick (St. John), and Eastern Newfoundland (Avalon). With these typical rocks are correlated part of the limestones of Dutchess County, New York (Stissing) and the central parts of the Tennessee and Alabama sections (Coosa), with limestones in central Nevada and British Columbia (Mount Stephen).
Lower or Georgian (Olenellus fauna).	The typical locality is in western Vermont where shales and limestones are developed. With these are paralleled the quartzite of W. slope of Green Mountains and Appalachian chain in Pennsylvania, Virginia, Tennessee, Georgia, and Alabama; the shales and interbedded limestones and slates of S. Vermont and New York southward to Alabama; the limestone, sandstone, and shale of Straits of Belle Isle (Labrador), N.W. Coast of Newfoundland and peninsula of Avalon (Placentia); the basal series of Hanford Brook Section, Caton's Island, &c., New Brunswick; the shales and limestones of E. and S. Massachusetts (Attleborough); the lower portion of the Eureka and Highland ranges, Nevada (Prospect); a portion of the Wasatch Cambrian Section (Cottonwood) and the base of the Castle Mountain, British Columbia.

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[1] Walcott has found Olenellus about 2000 feet below the summit of the series, but he hesitates to assume that it can really range through such an enormous thickness of strata, 10th *Ann. Rep. U.S. Geol. Surv.* p. 583. See his later section in 12th *Ann. Rep.* (1892) plate xlii.

[2] A. Hague, *Ann. Rep. U.S. Geol. Surv.* 1881-82. Walcott, *Monogr. U.S. Geol. Surv.* vol. viii. (1884).

[3] C. D. Walcott, *Bull. U.S. Geol. Surv.* No. 81 (1891), p. 360.

A large assemblage of fossils has been obtained from the Cambrian rocks of North America. The fauna of the Olenellus-zone has been fully described in a separate monograph by Mr. Walcott. The middle group in New Brunswick (St. John) has also yielded an abundant fauna which has been described by Mr. Mathew.[1]

South America.—In the northern part of the Argentine Republic a representative of the Upper Cambrian or Olenus group has been found by Lorentz and Hyeronimus. It includes species of the genera *Lingula, Obolus, Orthis, Hyolithes, Arionellus, Agnostus,* and *Olenus.*[2]

China.—Baron von Richthofen has brought to light a succession of undisturbed strata (his 'Sinisian formation') which in Leao-tong and Corea attain a thickness of many thousand feet. In the higher parts of this series he found a characteristic assemblage of Primordial trilobites: *Conocoryphe* (*Conocephalites*) (4 sp.), *Anomocare* (6), *Liostracus* (3), *Dorypyge* (*Olenoides?*), *Agnostus* (1), with the brachiopods *Lingulella* (2) and *Orthis* (1).[3]

India.—In the Salt Range, among shales (Neobolus beds) underlying magnesian sandstones and shales with pseudomorphs of salt, and overlying purple sandstones, with a group of beds of rock-salt and gypsum, Cambrian fossils have been detected. They include a number of brachiopods (*Lingula, Davidsonella, Neobolus,* &c.) and two trilobites, one of which has been determined to be a *Conocephalites*, nearly related to *C. formosus* from the St. John's group (p. 736), while the other is probably an *Olenus.*[4]

Australia.—In the south-east of this continent and in Tasmania traces of the existence of a Cambrian fauna have recently been detected. Mr. R. Etheridge jun., has described from that region forms of *Conocephalites, Asaphus, Dikelocephalus* and *Ophileta,* and some species belonging to the family of Archæocyathinæ.[5]

Section ii. Silurian.

Murchison was the first to discover that the so-called "Transition rocks" or "Grauwacke" of early geological literature were capable of subdivision into distinct formations characterised by a peculiar assemblage of organic remains. As he found them to be well developed in the region once inhabited by the British tribe of Silures, he gave them the name of Silurian.[6] From the base of the Old Red Sandstone, he was able to trace his Silurian types of fossils into successively lower zones of the old "Grauwacke." It was eventually found that similar fossils characterised the older sedimentary rocks all over the world, and that the general order of succession worked out by Murchison could everywhere be recognised. Hence the term Silurian came to be generally employed to designate the rocks containing the first great fauna of the Geological Record.

The controversy regarding the respective limits of the Cambrian and Silurian formations (*ante*, p. 726) survived the lifetime of the two great antagonists. Professor Lapworth in 1879 proposed, as a compromise, that the lower half of Murchison's Silurian system, which Sedgwick had claimed as Cambrian, should be detached from both and erected into a distinct system under the name "Ordovician."[1] I consider that this proposal, which was honestly intended to obviate confusion and to promote the progress of the science, is fair to neither of these fathers of English geology, and is especially unjust to Murchison. The division of "Lower Silurian" has the claim not only of priority, but of having been established and of having had its component members defined by the author of the Silurian system in the early years of his investigation. The primordial fauna which Barrande had shown to underlie the Lower Silurian rocks of Bohemia was hardly known to exist in Britain during Murchison's life, and certainly was not then ascertained to have the stratigraphical significance and wide geographical diffusion which have now been proved. It is universally admitted that this fauna marks a distinct section of the geological record to which by common consent the name Cambrian is given. The upper limit of this fauna is likewise recognised. So that it is not a question of fact but of nomenclature which is in dispute. With the modification of the accepted base-line at the top of the Tremadoc Slates, I shall continue to employ the terminology proposed by the illustrious author of the "Silurian System" as being quite adequate for the most recent requirements of investigation.[2]

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[1] Walcott, 10th *Ann. Report U.S. Geol. Surv.* (1890), where plates and descriptions of the fossils will be found. See also his papers in *Bull. U.S. Geol. Surv.* Nos. 10 and 30. For the fossils of the St. John division consult the papers of G. F. Mathew, quoted on p. 735.

[2] E. Kayser, "Beitrage zur Geol. u. Palaeont. d. Argentinischer Republik. Part II. (1876).

[3] R'chthofen, 'China,' vol. iii. (1882). W. Dames compares this Chinese Cambrian fauna with that of the Andrarumskalk of Scandinavia: *op. cit.* p. 32 (*ante*, p. 731). Mr. Walcott inclines to believe that the fossils rather point to a Middle Cambrian fauna (*Bull. U.S. Geol. Surv.* No. 81, 1891, p. 379).

[4] *Palæontologia Indica*, ser. 13, vol. i. (1887) p. 750.

[5] *Proc. Roy. Soc. Tasmania*, 1882-83, p. 151; *Trans. Roy. Soc. South Australia*, xiii. (1890) p. 10.

[6] *Phil. Mag.* (3) vii. (1835) p. 47.

§ 1. General Characters.

ROCKS.—The Silurian system consists usually of a massive series of greywackes, sandstones, grits, shales, or slates, with occasional bands of limestone. The arenaceous strata include pebbly grits and conglomerates, which are specially apt to occur at or near any local base of the formation, where they rest unconformably on older rocks. Occasional zones of massive conglomerate occur, as among the Llandovery rocks of Britain. The argillaceous strata are in some regions (Livonia, &c.) mere soft clays: most commonly they are hard fissile shales, but in some areas (Wales, &c.), where they have been subjected to intense compression, they appear as hard cleaved slates, or even as crystalline schists. In Europe, the limestones are, as a rule, lenticular, as in the examples of the Bala, Aymestry, and Dudley bands, though in the basin of the Baltic, some of the limestones have a greater continuity. In North America, on the other hand, the Trenton limestones in the Lower, and the Niagara limestone in the Upper Silurian division are among the most persistent formations of the eastern United States and Canada, while in the Western Territories vast masses of Silurian limestone constitute nearly the whole of the system. Easily recognisable bands in many Silurian tracts, especially in the north-west of Europe, are certain dark anthracitic shales or schists, which, though sometimes only a few feet thick, can be followed for many leagues. As they usually contain much decomposing iron-disulphide, which produces an efflorescence of alum, they are known in Scandinavia as the alum-slates. In Scotland, they are the chief repositories of the Silurian graptolites. Their black, coal-like aspect has led to much fruitless mining in them for coal. In the northern part of the State of New York, a series of beds of red marl with salt and gypsum occurs in the Upper Silurian series. In the Salt Range of the Punjab the group of saliferous strata occurs which has been already alluded to in the account of the Cambrian rocks. These salt-bearing deposits are the oldest yet discovered. In Styria and Bohemia, important beds of oolitic hæmatite and siderite are interstratified with the ordinary greywackes and shales. Occasionally sheets of various eruptive rocks (felsites, diabases, diorites, &c.) occur contemporaneously imbedded in the Silurian rocks (Wales, Lake District, S. Scotland, S.E. Ireland, &c.), and, with their associated tuffs, represent the volcanic ejections of the time.

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[1] *Geol. Mag.* 1879, p. 13.

[2] The reader who would peruse a weighty and dispassionate examination of this disputed question in geological nomenclature should turn to the essay by the venerable Professor J. D. Dana on "Sedgwick and Murchison; Cambrian and Silurian" (*Amer. Journ. Sci.* xxxix. 1890, p. 167). With the conclusions of his examination of the whole question I most thoroughly agree.

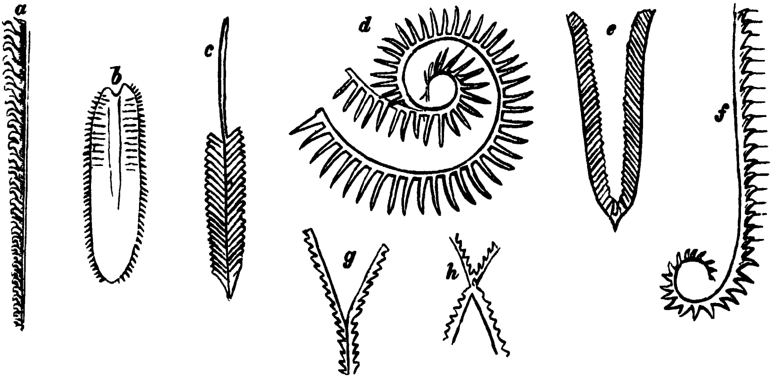

Fig. 340.—Group of Silurian Graptolites.

a, Monograptus priodon, Bronn (Wenlock); *b*, Phyllograptus typus, Hall (Lower Arenig); *c*, Diplograptus folium, His. (Llandovery); *d*, Rastrites peregrinus, Barr (Llandovery); *e*, Didymograptus Murchisoni, Beck. (Llandeilo); *f*, Monograptus Sedgwickii, Portl. (Llandovery); *g*, Dicranograptus ramosus, Hall (Llandeilo); *h*, Tetragraptus Hicksii, Hopk. (Lower Arenig).

As a rule, Silurian rocks have suffered from subsequent geological revolutions, so that they now appear inclined, folded, contorted, broken, and cleaved, sometimes even metamorphosed into crystalline schists. In certain regions, however (Basin of the Baltic, New York, &c.), they still remain nearly in their original undisturbed positions.

LIFE.—The general aspect of the life of the Silurian period, so far as it has been preserved to us, may be gathered from the following summary published by Bigsby in 1868—plants 82 species; amorphozoa 136; foraminifera 25; cœlenterata 507; echinodermata 500; annelida 154; cirripedes 8; trilobita 1611; entomostraca 318; polyzoa 441; brachiopoda 1650; monomyaria 168; dimyaria 541; heteropoda 358;

gasteropoda 895; cephalopoda 1454; pisces 37; class uncertain 12; total 8897 species. Barrande in 1872 published another census in which some variations are made in the proportions of this table, the total number of species being raised to 10,074, which has subsequently been still further increased.

The plants as yet recovered are chiefly fucoids. In many cases they occur as mere impressions, which are often probably not of vegetable origin at all, but casts of the trails or burrows of worms, crustacea, &c.[1] Among the most abundant genera are *Buthotrephis*, *Arthrophycus*, *Palæophycus*, and *Nematophycus* (Carruth.) But in the Upper Silurian rocks beautifully preserved sea-weeds like the living *Gelidium* or *Plocamium* occur, such as the *Chondrites verisimilis* (Salt.) of the Ludlow rocks of Edinburghshire. Traces, however, of a higher vegetation have been discovered, which are of special interest as being the earliest known remains of a land-flora. Many years ago certain minute bodies (*Pachytheca*) in the Ludlow bone-bed were regarded as lycopodiaceous spore-cases, but some doubt has been cast on their organic grade. More recently, Dr. Hicks obtained from the Denbighshire grits of N. Wales other spores and likewise dichotomous stems, probably lycopodiaceous.[2] True lycopods (*Sagenaria*) have been met with in the Upper Silurian rocks of Bohemia. From the Clinton limestone of Ohio portion of a lepidodendroid tree (*Glyptodendron eatonense*) has been obtained. The Cincinnati group of strata, at the top of the Lower, and the Lower Helderberg at the top of the Upper Silurian formations of eastern North America, have yielded a microcosmical representation of the Carboniferous flora. The genera noted include *Psilophyton*, *Calamophycus*, *Annularia*, *Protostigma*, *Sigillaria*, and *Sphenophyllum*.[3] From the meagre evidence as yet collected, it would appear that the land of the Silurian period had a cryptogamic vegetation in which lycopods and ferns no doubt played the chief part.[4]

In the fauna of the Silurian rocks, the most lowly organisms known are foraminifera, of which several genera, including the still living genus *Saccammina*, have been detected. Certain layers of chert, widely spread over the south of Scotland, have yielded upwards of a dozen genera with more than twenty species of radiolaria.[5] The Silurian seas possessed representatives both of the calcareous and of the siliceous sponges of modern times. Under the former group may be placed the genus *Archæocyathus* which occurs in the Cambrian system, and the genera *Astræospongia* and *Amphispongia* of the Upper Silurian rocks; under the latter group come

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[1] Nathorst (*Kongl. Svensk. Vet. Akad. Handl.* xviii. (1881) has imitated some of these markings by causing crustacea, annelids, and mollusks to move over wet mud and gypsum, and has thus shown the high probability that they are not plants. (See *Geol. Mag.* 1882, pp. 22, 485; 1883, pp. 33, 192, 286.) Nathorst's opinion, adverse to the plant nature of the markings, is strongly opposed by Saporta in his 'À propos des Algues Fossiles,' 1882.

[2] *Q. J. Geol. Soc.* 1881, p. 482; 1882, pp. 97, 103.

[3] L. Lesquereux, *Amer. Journ. Sci.* (3) vii. p. 31; *Proc. Amer. Phil. Soc.* xvii. p. 163.

[4] The student will find a valuable compendium of information by L. F. Ward regarding the fossil floras of past time all over the world in the 8th *Ann. Rep. U.S. Geol. Surv.* part ii. 1889.

[5] G. J. Hinde, *Ann. Mag. Nat. Hist.* 1890, p. 40.

Astylospongia and *Protachilleum*. Of the puzzling genera *Receptaculites* and *Ischadites*, the true relationships have not yet been determined. *Nidulites*, too, though a common fossil, is still a subject of uncertainty as to its organic grade, the latest view being that it may be related to the polyzoa.

Some of the most plentiful and characteristic denizens of the Silurian seas were undoubtedly the various hydrozoan genera united under the common name of graptolites (Fig. 340).[1] Among the monoprionidian forms, or those with a single row of cells, the genera *Monograptus* (of which upwards of 40 species have been found in Britain), *Rastrites* and *Cyrtograptus* are characteristic of Upper Silurian rocks. The diprionidian forms, or those with two rows of cells, are equally characteristic of the lower subdivision of the Silurian system, and are richest in genera, of which some of the commonest are *Dicellograptus*, *Didymograptus*, and *Tetragraptus*.

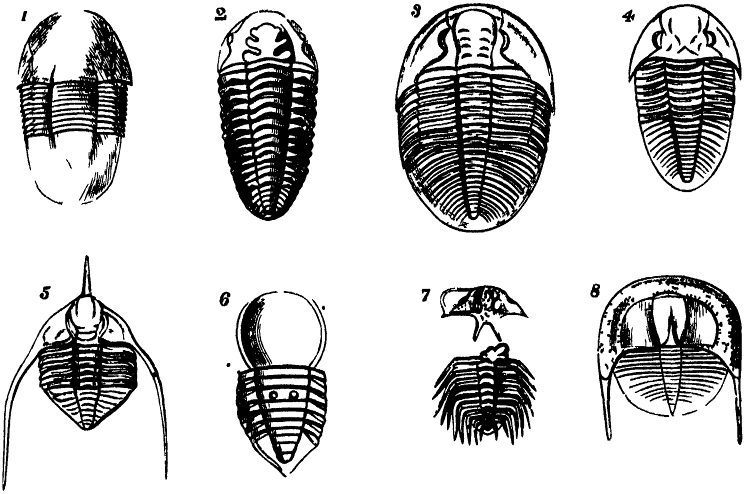

Fig. 341.—Group of Lower Silurian Trilobites.

1, Illænus Davisii, Salt. (½), 2, Calymene brevicapitata, Portl., 3, Ogygia Buchii, Brongn. (¼), 4, Asaphus tyrannus, Murch. (⅓), 5, Ampyx nudus, Murch. (½), 6, Æglina binodosa, Salt., 7, Acidaspis Jamesii, Salt., 8, Trinucleus Lloydii, Murch.

Graptolites were formerly supposed to belong exclusively to Silurian rocks; but it has already been pointed out that they descend into the Cambrian system. Nevertheless it was in Silurian time that they reached their maximum development. A few genera (*Diplograptus*, *Climacograptus*, *Retiolites*) occur both in the Lower and Upper Silurian strata, though the species are not persistent. Through the researches chiefly of Professor Lapworth it has been ascertained that the vertical range of the species of graptolites is comparatively limited, and hence that these fossils may be used to mark definite palæontological horizons. He enumerates twenty recognisable graptolite zones, one in the Upper Cambrian, eight in the Lower Silurian, and eleven in the Upper Silurian formations.[1] The peculiar form *Stromatopora* and several allied genera are now referred to the Hydrozoa.

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[1] The student should consult Professor Lapworth's Monograph "On the Geological Distribution of the Rhabdophora" (*Ann. Mag. Nat. Hist.* ser. 5, vols. iii. iv. v. and vi. 1879, 1880) in which the geological significance of the graptolites is fully discussed.

Corals must have swarmed on those parts of the Silurian sea-floor on which calcareous accumulations gathered, for their remains are abundant among the limestones, particularly in the upper division of the system. Among the tabulate forms are the genera *Favosites*, so characteristic in the Upper Silurian limestones of Europe and America, *Chætetes*, *Thecia*, *Halysites* or chain coral, *Syringopora*, and *Tetradium*. The rugose corals are likewise abundant, some conspicuous genera being *Stauria*, *Cyathaxonia*, *Cyathophyllum*, *Zaphrentis*, *Petraia*, *Omphyma*, *Strombodes*, *Ptychophyllum*, and *Acervularia* (Fig. 345). The echinoderms were represented by star-fishes (*Palæaster*, *Palæasterina*, *Palæocoma*, *Lepidaster*), brittle-stars (*Protaster*, *Eucladia*), many forms of crinoids (*Actinocrinus*, *Cyathocrinus*, *Glyptocrinus*, *Eucalyptocrinus*, *Taxocrinus*, &c.), and particularly by species of cystideans (*Echinosphærites*, *Sphæronites*, *Pleurocystites*, *Hemicosmites*). The annelides of the Silurian sea-bottom comprised representatives of both the tubicolar and errant orders. To the former belong the genera *Cornulites*, *Ortonia*, *Conchicolites*, *Serpulites*, and also the still living genus *Spirorbis*. The errant forms are known chiefly by their burrows or trails, which appear in immense profusion on the surfaces of shales and sandstones (*Arenicolites*, *Nereites*, *Scolithus*, &c.), but also by their jaws, which occur in great numbers in the Wenlock and Ludlow rocks.[2]

The crustacea of the period have been abundantly preserved and form some of the most familiar and distinctive fossils of the system. Undoubted cirripedes have been found in the Silurian rocks of Britain, Bohemia, and North America (*Turrilepas*, *Anatifopsis*). Small ostracods abound in certain shales, some of the most frequent genera being *Entomis*, *Beyrichia*, *Primitia*, *Leperditia*, *Aristozoe*, *Orozoe*, *Callizoe*. The phyllopods, which, as we have seen, made their appearance in Cambrian times, continue to occur on scattered horizons, and generally not in great numbers, throughout the Lower and Upper Silurian rocks; characteristic genera are *Caryocaris*, *Peltocaris*, *Discinocaris*, *Ceratiocaris*, *Dictyocaris*, *Cryptocaris*, and *Aptychopsis*. But by far the most prolific order is that of the trilobites (Figs. 341, 345), which, beginning in the Cambrian, attained its maximum development in the Silurian, waned in the Devonian, and became extinct in the Carboniferous period. According to the census of Barrande in 1872 there were then 1579 known species, but this number has since been greatly increased. With a few exceptions the Cambrian genera did not survive into Silurian time (p. 730). They were succeeded by many new genera which continued to live through most of the Silurian period. In the lower division of the system, characteristic genera are

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[1] *Op. cit.* v. (1880) p. 197. O. Jaekel (*Zeitsch. Deutsch. Geol. Ges.* 1889, p. 653) has recently proposed to distinguish the monograptidæ in two groups, *Pristiograptus* characterising the older and *Pomatograptus* the later parts of the Upper Silurian series.

[2] G. J. Hinde, *Q. J. Geol. Soc.* 1880, p. 368; *Bihang. Svensk. Vet. Akad. Handl.* vi. (1882).

Æglina, *Asaphus*, *Amphion*, *Ampyx*, *Barrandia*, *Chasmops*, *Cybele*, *Harpes*, *Ogygia*, *Placoparia*, *Remopleurides*, and *Trinucleus*; some genera are common to both the lower and upper divisions (but usually with specific distinctions), such as *Acidaspis*,* *Bronteus*,* *Calymene*, *Cheirurus*, *Cyphaspis*, *Dalmanites*, *Encrinurus*,* *Homalonotus*,* *Illænus*, *Lichas*, *Phacops*,*[1] and *Sphærexochus*. *Proetus* is confined to the upper division. Towards the top of the system eurypterids make their appearance, and continue to occupy a prominent place until the Carboniferous period. The Silurian genera are *Pterygotus*, *Eurypterus*, *Slimonia*, *Stylonurus*, and *Hemiaspis*.

The polyzoa of Silurian times have been tolerably well preserved, and present many peculiarities of structure. One of the most abundant genera is *Fenestella*, which ranges from Lower Silurian to Permian rocks; another, *Ptilodictya*, ascends into the Carboniferous system. Other genera are *Retepora*, *Paleschara*, and *Hippothoa*. So abundant are the brachiopods (many hundreds of species being known), and so characteristic on the whole are the species of them occurring in certain Silurian zones or bands, that these fossils must be regarded as of special value for purposes of stratigraphical comparison.[2] The old and still living genera *Discina*, *Lingula*, and *Crania* are found on different horizons in the Silurian series. Characteristic types are *Acrotreta*, *Atrypa*, *Leptæna*, *Meristella*, *Orthis* (Figs. 342, 343), *Pentamerus* (Fig. 344), *Porambonites*, *Rhynchonella* (Fig. 346), *Siphonotreta*, *Spirifer*, *Stricklandinia*, *Strophomena* (Fig. 346), and *Triplesia*. Some of these are particularly distinctive of certain zones. Thus, from the abundance of *Pentameri* in them, certain strata received the name of the "Pentamerus beds" (Fig. 344). *Orthis* is most abundant in species in the lower part of the Silurian system: *Pentamerus*, *Rhynchonella*, *Spirifer*, *Chonetes*, and *Terebratula*, occur in the upper. The

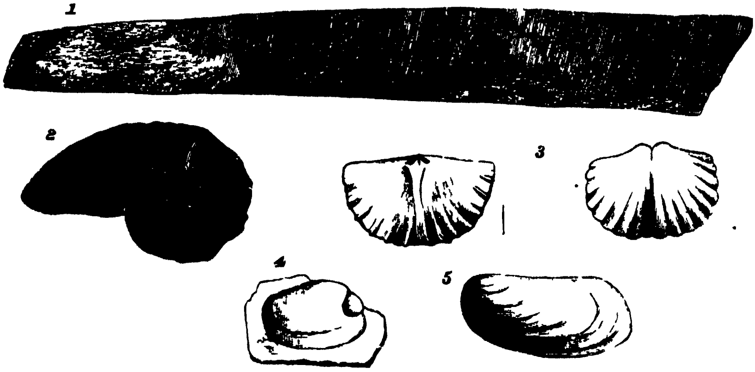

Fig. 342 —Group of Arenig Fossils

1, Orthoceras cæreesiense, Hicks ; 2, Bellerophon llanvirnensis, Hicks ; 3, Orthis calligramma, Dalm (enlarged) ; 4, Redonia anglica, Salt ; 5, Palæarca amygdalus, Salt lamellibranchs have been less abundantly preserved; some of their most frequent genera are the monomyarian *Ambonychia* (Fig. 343) and *Pterinea* and the dimyarian *Ctenodonta*, *Modiolopsis*, *Goniophora*, *Orthonota* (Fig. 346), *Cleidophorus* (Fig. 343), *Palæarca*, and *Redonia* (Fig. 342). *Cardiola interrupta* (Fig. 346) is a characteristic shell of the highest Upper Silurian rocks.

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[1] Those genera marked with * are more characteristic of the Upper than of the Lower Silurian strata.

[2] For an account of the internal arrangements of some Silurian brachiopods and a list of the Upper Silurian species of England, see Davidson, *Geol. Mag.* 1881, pp. 1, 100, 145, 289.

Of the gasteropods of the Silurian seas upwards of 1300 species have been named; some of the more frequent genera are *Acroculia*, *Cyclonema*, *Euomphalus* (Fig. 346), *Helicotoma*, *Holopæa*, *Holopella*, *Murchisonia*, *Ophileta*, *Platyschisma*, *Pleurotomaria*, *Raphistoma*, *Trochus* (Fig. 346), and *Subulites*. Some heteropod forms occur, *e.g.* *Bellerophon* and *Maclurea*; but pteropods are more frequent, being represented sometimes abundantly by the genera *Tentaculites* (regarded by some as an annelide), *Hyolithes* (or *Theca*), *Conularia*, and *Pterotheca*. That the salt waters of the Silurian era swarmed with cephalopods may be inferred from the fact that according to Barrande's census no fewer than 1622 species had then been described. They are all tetrabranchiate. Some of the most abundant forms are straight shells, of which *Orthoceras* (Figs. 342, 346) is the type. This characteristically Palæozoic genus abounded in the Silurian period, when many of its individuals attained a great size. Barrande has described upwards of 550 species from the basin of Bohemia. Of *Cyrtoceras*, in which the shell was curved, the same small area has yielded more than 330 species. *Phragmoceras* (Fig. 346) likewise possessed a curved shell, but with an aperture contracted in the middle. In *Ascoceras* the shell was globular or flask-shaped, with curiously curved septa; in *Lituites* (Fig. 346) it was curled like that of *Nautilus*. The two latter genera occur in Silurian rocks, but while *Lituites* never outlived the Silurian period, *Nautilus* is still a living denizen of the sea.

The first traces of vertebrate life make their appearance in the Silurian system. They consist of the remains of fishes, the most determinable of which are the plates of placoderms (*Pteraspis*, *Cephalaspis*, *Auchenaspis*, *Scaphaspis*). The bone-bed of the Ludlow rocks has also yielded certain curved spines (*Onchus*), which have been referred to a cestraciont, and some shagreen-like plates which have been supposed to be scales of placoid fishes (*Sphagodus*, *Thelodus*), and bodies like jaws with teeth which were called *Plectrodus*, but which are now known to be lateral shield-spines of a cephalaspidean fish (*Eukeraspis*). It is probable that some of these remains have been incorrectly determined, and may belong to crustaceans or annelides. The Upper Silurian rocks have yielded, both in Europe and North America, great numbers of minute tooth-like bodies which were named "Conodonts" by their discoverer, Pander, and were supposed to be the teeth of such fishes as the lamprey, which possessed no other hard parts for preservation. These bodies have been also referred to different divisions of the invertebrata, but palæontologists now regard them as probably in most cases the jaws of annelids.[1]

Satisfactory evidence of the occurrence of fishes in rocks of Silurian age is supplied by Mr. Walcott, who has described from the Lower Silurian rocks of Cañon City, Colorado, a number of fish remains, among which he has been able to identify dermal plates and scales belonging to genera like *Asterolepis* and *Holoptychius*, which play so important a part in the Devonian fauna.[1] According to Dr. J. V. Rohon, all the so-called "Conodonts" are not annelidian, but include undoubted teeth of fishes with recognisable dentine, enamel, and pulp-cavity. He describes from the Glauconite Sand of St. Petersburg forms belonging to two new genera named by him *Palæodus* and *Archodus*.[2]

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[1] Zittel and Rohon, *Sitzb. Bayr. Akad.* Munich, 1886, p. 108.

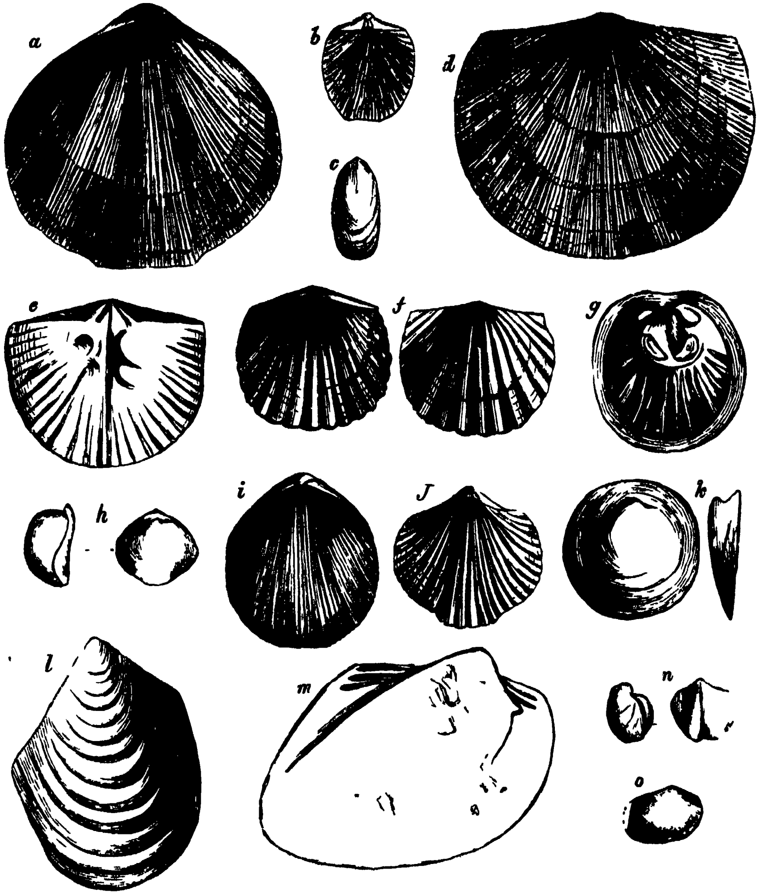

Fig. 343.—Group of Caradoc Fossils.

a, Porambonites intercedens, Pander; *b*, Orthis hirnantensis, McCoy; *c*, Lingula longissima, Pander (?); *d*, Strophomena grandis, Sby.; *e*, Orthis plicata, Sby.; *f*, Orthis calligramma, Dalm.; *g*, Crania divaricata, McCoy; *h*, Triplesia (?) maccoyana, Dav.; *i*, Atrypa (?) Headii, Billings (?); *j*, Atrypa marginalis, Dalm.; *k*, Discina oblongata, Portl.; *l*, Ambonychia prisca, Portl.; *m*, Palæarca billingsiana, Salt.; *n*, Rhynchonella nana, Salt.; *o*, Cleidophorus ovalis, McCoy.

Up to the present time no trace has been detected of any vertebrate land-animals of Silurian age. In Sweden, France, Scotland, and the United States, however, the discovery of remains of arachnid and insect life in Silurian rocks may herald the ultimate detection of higher forms of life. From the Upper Silurian strata of the island of Gothland a true scorpion has been discovered, which appears to differ in no essential respect from recent forms, except in the walking limbs, which are dumpy in form, and terminate in a single claw. One of the breathing stigmata on the second ventral scute shows clearly that the animal was an air-breather.[1] Subsequently a still more perfect example of the same genus (*Palæophoneus*) was described from the Upper Silurian rocks of Lesmahagow, Lanarkshire (Fig. 347). The presence of a poison-gland and sting at the extremity of the tail shows that, like their modern representatives, these ancient animals preyed on other denizens of the land. Soon after the European discoveries, the finding of a scorpion in the "Waterlime" (Upper Silurian) of New York was announced.[2] These specimens lifted the veil that had concealed from us all evidence of the terrestrial fauna of this ancient period of geological history. If there were scorpions on the land, there were almost certainly other land-animals on which they lived. Mr. Peach has suggested that they may have fed partly on marine crustacean eggs left bare by the tides.[3] But that insects already existed has been made known by the discovery of a true insect-wing in the Lower Silurian (probably Caradoc) sandstone of Jurques, Calvados.[4] It measures about 1½ inch long, and is distinguished by the length of the anal nervure and the small breadth of the axillary area. It is a primeval form of *Blatta*, and has been named by M. Brongniart *Palæoblattina*. We may be confident that these are not the only relics of the Silurian terrestrial fauna that have been preserved, and we may hope that still more remarkable treasures are yet to be unearthed from their primeval resting-places.

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[1] *Bull. Geol. Soc. America*, iii. (1892) p. 153.

[2] J. V. Rohon, *Bull. Acad. Imp. Sci. St. Pétersbourg*, xxxiii. 1890, p. 269.

§ 2. Local Development.

Britain.[5]—In the typical area where Murchison's discoveries were first made, he found the Silurian rocks divisible into two great and well-marked series, which he termed Lower and Upper. This classification has been found to hold good over a large part of the world. The subjoined table shows the arrangement and nomenclature of the various subdivisions of the Silurian system :—

			Feet
Upper Silurian.	6. Ludlow group .	approximate average thickness	1900
	5. Wenlock group .	,,	1600
	4. Llandovery group	,,	3000
Lower Silurian.	3. Bala and Caradoc group	,,	6000
	2. Llandeilo group .	,,	3000
	1. Arenig group .	,,	4000
		,,	19,500

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[1] G. Lindstrom, *Comptes rend.* xcix. (1884) ; T. Thorell and G. Lindstrom, *K. Svensk. Vet. Akad. Handl.* xxi. No. 9 (1885).

[2] R. P. Whitfield, *Science*, vi. (1885) p. 87.

[3] B. N. Peach, *Nature*, xxxv. (1885) p. 295 ; *Trans. Roy. Soc. Edin.* xxx. (1882).

[4] Ch. Brongniart, *Comptes rend.* xcix. (1884) p. 1164 ; *Geol. Mag.* (1885) p. 481.

[5] See Murchison's 'Silurian System,' and 'Siluria' ; Sedgwick's 'Synopsis' (cited

a. Lower Silurian.

The typical subdivisions in Wales and Shropshire will first be described, and afterwards the development of the series in other parts of Britain.

1. Arenig Group.—These rocks consist of dark slates, shales, flags, and bands of sandstone. They are abundantly developed in the Arenig mountain, where, as originally described by Sedgwick, they include masses of associated volcanic rocks. In their abundant suite of organic remains new genera of trilobites make their appearance (*Æglina, Barrandia, Calymene, Homalonotus, Illænopsis, Illænus, Phacops, Placoparia, Trinucleus*). Pteropods are represented by species of *Conularia* and *Theca*; brachiopods by *Lingula, Lingulella, Obolella, Discina, Siphonotreta,* and *Orthis*; lamellibranchs by *Palæarca* and *Ribeiria*; gasteropods by *Ophileta* and *Pleurotomaria*; heteropods by *Bellerophon* and *Maclurea*; and cephalopods by *Orthoceras.* But the most abundant organisms are the graptolites, of which no fewer than twenty genera have been found in the Arenig rocks of Britain. In the lower part of the group the genus *Tetragraptus* is especially characteristic, for it is not at present known to occur on any higher or lower horizon. Here lies the lowest Silurian graptolitic zone, that of *Tetragraptus bryonoides.* The genera *Loganograptus, Clonograptus, Schizograptus,* and *Dichograptus* are probably also peculiar to the same strata, as well as the species *Didymograptus extensus, D. pennatulus,* and the only known examples of *Retiograptus.* The upper part of the Arenig group (zone of *Didymograptus bifidus*) is especially marked by the presence of *Phyllograptus,* in association with forms of *Dichograptus* like *D. bifidus.* Species peculiar to it, besides the last-named, are *D. minutus* and some forms of Diplograpta, such as *Climacograptus confertus.*[1]

Dr. Hicks has proposed to construct a separate group under the name of "Llanvirn," by taking the upper part of the Arenig and lower portion of the Llandeilo rocks, making a total thickness of about 2000 feet of strata near St. David's in South Wales.[2] It is in this group of strata that the trilobites *Acidaspis, Barrandia, Illænus,* and *Phacops* make their earliest appearance. Sir A. C. Ramsay believed that in North Wales there is an unconformable overlap of the Arenig upon the Tremadoc and older beds; but in South Wales there does not appear to be any break.[3]

A remarkable feature in the history of the Arenig rocks in Wales was the volcanic action during their formation, whereby various felsitic or rhyolitic lavas, with abundant discharges of fine ashes and coarser agglomerates, were erupted over the sea-bottom and interstratified with the contemporaneously deposited sediments, while more basic sills were subsequently injected under the volcanic sheets. Some of the more important Welsh mountains consist mainly of these ancient volcanic materials—Cader Idris, the Arans, Arenig Mountain, and others.[4]

2. Llandeilo Group.—These dark argillaceous and occasionally calcareous flagstones, sandstones, and shales were first described by Murchison as occurring at Llandeilo, in Carmarthenshire. They reappear near St. David's, on the coast of Pembrokeshire, and at Builth, in Radnorshire. In the lower subdivision of them a seam of limestone occurs, while intercalated igneous rocks are specially noticeable in the upper subdivision. It was at one time believed that graptolites were almost confined to this

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p. 725); Ramsay's 'North Wales' in *Memoirs of Geol. Surv.* vol. iii.; Etheridge, Address, *Q. J. Geo' Soc.* 1881; numerous local memoirs in recent volumes of the *Q. J. Geol. Soc.* and *Geol. Mag.*, particularly by Hicks, Ward, Hughes, Keeping, Lapworth, &c.

[1] Lapworth, *Ann. Mag. Nat. Hist.* vol. vi. (1880) p. 197.

[2] *Pop. Science Rev.* (1881) p. 289.

[3] 'Geology of N. Wales,' *Mem. Geol. Surv.* iii.

[4] For descriptions of the Arenig lavas and tuffs consult the 'Geology of N. Wales' already cited; also G. A. Cole and C. V. Jennings, *Quart. Journ. Geol. Soc.* xlv. (1889). *Geol. Mag.* (1890) p. 447; Jennings and G. J. Williams, *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 374. *Op. cit.* Presidential Address, p. 105.

group. These fossils, now known to range from the Cambrian to the top of the Silurian system, occur abundantly in the Llandeilo rocks, and present there a transitional character between the Arenig types below and those in the Caradoc or Bala rocks above. In the lower portions of the group the most abundant genus is *Didymograptus*, *D. Murchisoni* being the characteristic species (and serving to mark a graptolitic zone) accompanied by many of the Arenig species, together with new forms of *Cryptograptus* and *Glossograptus*. In the middle part of the group the *D. Murchisoni* becomes very rare and is associated with *Diplograptus foliaceus* and *Climacograptus Scharenbergi*. In the Upper Llandeilo rocks graptolites of the type of *Cryptograptus tricornis* and *Climacograptus Scharenbergi* are abundant, also species of *Cœnograptus* with *Dicellograptus sectans* (zone of *Cœnograptus gracilis*). Trilobites are characteristic fossils of the group, upwards of fifty species belonging to eighteen or twenty genera being known. These include characteristic forms which do not range beyond the group, *Asaphus tyrannus*, *Calymene cambrensis*, *Trinucleus Lloydii*, and *T. favus* being found in the lower subdivision, and *Barrandia Cordai*, *Cheirurus Sedgwickii*, and *Ogygia Buchii* in the upper. The phyllopod *Peltocaris aptychoides* is also peculiar. The brachiopods include the genera *Acrotreta*, *Crania*, *Discina*, *Leptæna*, *Lingula*, *Orthis*, *Rhynchonella*, and *Strophomena*, some of which here make their first appearance. The lamellibranchs are represented by species of *Cardiola* (*C. interrupta*) and *Modiolopsis* (*M. expansa*, *M. inflata*), the gasteropods by *Cyclonema*, *Euomphalus*, *Murchisonia*, *Pleurotomaria*, *Raphistoma*, and *Turbo*, the heteropods by *Bellerophon*, *Ecculiomphalus*, and *Maclurea*, the pteropods by *Conularia* and *Theca*, the cephalopods by *Cyrtoceras*, *Orthoceras*, and *Endoceras*.

3. Caradoc and Bala Group.—Under this name were placed by Murchison the thick yellowish and grey sandstones of Caer Caradoc in Shropshire, and the Horderley and May Hill Sandstone. It was afterwards ascertained that the grey and dark slates, grits, and sandstones, described by Sedgwick as occurring round Bala in Merionethshire and regarded by him as the higher part of his Cambrian system, were really slightly different lithological developments of the same stratigraphical division. In the Shropshire area, some of the rocks are so shelly as to become strongly calcareous. In the Bala district, the strata contain two limestones separated by a sandy and slaty group of rocks 1400 feet thick. The lower or Bala limestone (25 feet thick) has been traced as a variable band over a large area in North Wales. It is usually identified with the Coniston limestone of the Westmoreland region. The upper or Hirnant limestone (10 feet) is more local. Bands of volcanic tuffs and large beds of various felsitic lavas occur among the Bala beds, and prove the contemporaneous ejection of volcanic products. These attain a thickness of several thousand feet in the Snowdon region.[1]

A large suite of fossils has been obtained from this group. The sponges are represented by *Sphærospongia*, *Acanthospongia*, and other genera. The graptolites are strongly differentiated from those of the Arenig rocks by the entire absence of Dichograptidæ and Phyllograptidæ. The Diplograptidæ, feebly represented in the Arenig and Lower Llandeilo groups, are now, as Professor Lapworth points out, the dominant forms, occurring in swarms in every zone. The two genera *Diplograptus* and *Climacograptus* are especially abundant. The following successive zones each marked by the prevalence of its own species of graptolite have been observed by Professor Lapworth in ascending order: (1) Zone of *Climacograptus Wilsoni*, (2) Zone of *Dicranograptus Clingani*, (3) Zone of *Pleurograptus linearis*, (4) Zone of *Dicellograptus complanatus*, (5) Zone of *Dicellograptus anceps*. The same observer remarks upon the extraordinary extinction of families, genera, and species of graptolites during the period of the Caradoc-Bala rocks.

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[1] For accounts of the volcanic phenomena of the Caradoc-Bala series of Wales, see A. C. Ramsay's 'Geology of North Wales,' forming vol. iii. of the General Memoirs of the Geological Survey; Harker's 'Bala Volcanic Series of Cærnarvonshire,' being the Sedgwick Prize Essay for 1888; F. Rutley, *Quart. Journ. Geol. Soc.* xxxv. (1879) p. 508; W. W. Watts, *op. cit.* xli. (1885) p. 532; and vol. xlvii. (1891) Presidential Address, p. 117.

"The entire families of the Dicranograptidæ, Leptograptidæ, and Lasiograptidæ, disappear from sight altogether. The only families that survive into the Llandovery rocks are those of the Diplograptidæ and Retiolitidæ, and these only in a very degenerate form." Yet it is remarkable that it was during Caradoc time that the Dicranograptidæ and Leptograptidæ attained their highest development.[1]

To the conditions that allowed the deposition of limestone bands in this group we doubtless owe the presence of upwards of 40 species of corals (Fig. 345) belonging to *Alveolites*, *Cyathophyllum*, *Favosites*, *Halysites*, *Heliolites*, *Monticulipora*, *Omphyma*, *Petraia*, &c. The echinoderms are represented by encrinites of the genera *Actinocrinus*, *Cyathocrinus*, and *Glyptocrinus*, by no fewer than 16 species of cystideans (*Echinosphærites*, *Sphæronites*, *Agelacrinites*, *Hemicosmites*, &c.), and by star-fishes of the genera *Palæaster*, *Protaster*, and *Stenaster*; the annelides by *Serpulites*, and numerous burrows and tracks; the trilobites by species of *Acidaspis* (7 species), *Ampyx* (6), *Asaphus* (6), *Calymene* (5), *Cheirurus* (6), *Cybele* (2), *Encrinurus* (3), *Homalonotus* (4), *Illænus* (9), *Lichas* (5), *Phacops* (15), *Remopleurides* (7), *Trinucleus* (6); the ostracods by *Beyrichia*, *Leperditia*, *Cythere*, *Primitia*, and *Entomis*; the polyzoa by *Fenestella*, *Glauconome*, *Ptilodictya*, and *Retepora*; the brachiopods by *Atrypa*, *Rhynchonella*, *Meristella*, *Leptæna* (10 species), *Orthis* (nearly 40), *Strophomena* (17), *Crania*, *Discina*, and *Lingula*; the lamellibranchs by *Ctenodonta* (17 species), *Orthonota* (5), *Modiolopsis* (15), *Pterinea* (6), *Ambonychia* (8), *Palæarca* (5); the gasteropods by *Murchisonia*, *Pleurotomaria*, *Raphistoma*, *Cyclonema*, *Euomphalus*, *Holopæa* and *Holopella*; the pteropods by *Tentaculites*, *Conularia*, *Theca*; the heteropods by species of *Bellerophon*, *Ecculiomphalus* and *Maclurea*; and the cephalopods by the genera *Orthoceras* (between 30 and 40 species), *Cyrtoceras*, *Lituites*, &c.

The Lower Silurian rocks, typically developed in Wales, extend over much of Britain, though largely buried under more recent formations. They rise into the hilly tracts of Westmoreland and Cumberland,[2] where they consist of the following subdivisions in descending order:—

Coniston Limestone series with the Ashgill shales above the limestone and the Dufton shales below it	=	Bala beds.
Borrowdale volcanic series (green slates and porphyries): tuffs and lavas without ordinary sedimentary strata except at base, 12,000 ft.	=	Part of Bala, whole of Llandeilo, and perhaps part of Arenig groups.
Skiddaw Slates, 10,000 or 12,000 ft., base not seen	=	Arenig group, with perhaps Tremadoc slates and Lingula Flags.

Apart from the massive intercalation of volcanic rocks, these strata present considerable lithological and palæontological differences from the typical subdivisions in Wales. The Skiddaw slates are black or dark-grey, argillaceous, and in some beds sandy rocks, often much cleaved, though seldom yielding workable slates, sometimes soft and black, like Carboniferous shale. As a rule, they are singularly unfossiliferous, but in some of their less cleaved and altered portions, they have yielded about 40 species of graptolites; *Lingula brevis*, traces of annelides, a few trilobites (*Æglina*, *Agnostus*, *Asaphus*, &c.), some phyllopods (*Caryocaris*), and remains of plants (?) (*Buthotrephis*, &c.) According to Professors Nicholson and Lapworth they may be provisionally divided into two groups, the lower consisting of dark flagstones and shales distinguished by species of *Tetragraptus*, *Didymograptus*, *Phyllograptus*, *Diplograptus*, *Loganograptus*, *Temnograptus*, *Schizograptus*, *Ctenograptus*, *Dichograptus*, and the upper made up of black shales and mudstones, containing some of the same and some different species of *Didymograptus* and *Phyllograptus*, and species of *Trigonograptus*, *Trichograptus*, *Glossograptus*, *Diplograptus*, and *Climacograptus*. The Skiddaw slates have been invaded by granite and other eruptive rocks, and display around these a well-marked contact-metamorphism (p. 605).

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[1] Lapworth, *Ann. Mag. Nat. Hist.* v. (1880) p. 358 *seq.*

[2] Sedgwick's "Three Letters addressed to W. Wordsworth," 1843; J. C. Ward, 'Geology of the North Part of the English Lake District' (*Geological Survey Memoir*) 1876; Nicholson, 'Essay on the Geology of Cumberland and Westmoreland,' 1868. See also papers by Harkness, Nicholson, Hughes, Marr and others in *Q. J. Geol. Soc.* and *Geol. Mag.*

Towards the close of the long period represented by the Skiddaw slates, volcanic action manifested itself, first by intermittent showers of ashes and streams of lava, which were interstratified with the ordinary marine sediment, and then by a more powerful and continuous series of explosions, whereby a huge volcanic mountain or group of cones was piled up above the sea-level. The vast pile of volcanic material (estimated at some 12,000 feet in total thickness) consists entirely of lavas and ashes without the interstratification of ordinary sediment except at the base and the top. The lower lavas are varieties of andesite, which are also met with in the central and higher parts of the Borrowdale volcanic series, while rhyolitic felsites were specially poured out towards the close of the volcanic period. Enormous quantities of fine volcanic ashes were likewise discharged. These various volcanic rocks form the picturesque hills of the Lake District.[1] The length of time occupied by this volcanic episode in Cumbrian geology may be inferred from the fact that all the Llandeilo and a large part of the Bala beds are absent here. The volcanic island slowly sank into a sea wherein Bala organisms flourished. In some places a group of shales occasionally 300 feet thick, and known as the Dufton shales, overlies the Borrowdale series, and contains among other characteristic species *Strophomena expansa*, *Leptæna sericea*, *Trinucleus concentricus*, *Homalonotus bisulcatus*, *Illænus Bowmanni*. The most marked rock of the overlying series is the Coniston limestone, which has yielded such familiar Bala species as *Favosites fibrosa*, *Heliolites interstinctus*, *Cybele verrucosa*, *Leptæna sericea*, *Orthis Actoniæ*, *O. biforata*, *O. calligramma*, *O. elegantula*, *O. porcata*, and *Strophomena rhomboidalis*. These organisms and their associates, gathering on the submerged flanks of the sinking volcano, before the eruptions had finally ceased, formed there the bed of limestone which is now traceable for many miles through the Westmoreland hills, like the Bala limestone of North Wales, which it probably represents. This Coniston limestone has an overlying conformable group of argillaceous strata (Ashgill shales) containing *Trinucleus concentricus*, *Phacops apiculatus*, *P. mucronatus*, *Strophomena siluriana*, and other Lower Silurian fossils. Not far to the east, at the base of the great Pennine escarpment, contemporaneous volcanic rocks in the Coniston series are well developed.[2] But the enormous volcanic group of Westmoreland and Cumberland dies out rapidly in that direction, for in the Craven district it is represented by a series of sandstones, grits and slates (often green), probably 10,000 feet thick, which passes up conformably into the Coniston limestone series.[3]

The Southern Uplands of Scotland are formed almost wholly of Lower and Upper Silurian strata which have been thrown into innumerable plications, often overthrust and reversed. The working out of this complicated structure has been made possible chiefly by the evidence furnished by certain zones of graptolitic shales, as has been well worked out by Professor Lapworth. The following table exhibits in descending order the subdivisions which have been established, with some of their characteristic fossils.[4]

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[1] On the volcanic geology of this region consult J. C. Ward in the work above cited; Presidential Address to Geological Society, *Quart. Journ. Geol. Soc.* 1891, p. 137, and authors there given.

[2] Harkness, *Q. J. Geol. Soc.* xxi. (1865) p. 235. Nicholson, *Geol. Mag.* 1869, p. 213. This "Crossfell inlier" has been described by Messrs. Nicholson, Marr, and Harker, *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 500.

[3] Hughes, *Geol. Mag.* iv. (1867) p. 346. This area had previously been described by Sedgwick, *Trans. Geol. Soc.* (2) iii. p. 1; and by Phillips, *Q. J. Geol. Soc.* viii. p. 35.

[4] See Lapworth, *Geol. Mag.* 1889, pp. 20, 59. The prolongation of the remarkable volcanic zone over the greater part of the Southern Uplands has been detected by Mr. B. N. Peach in the course of the Geological Survey.

	Leadhills and N.E. part of region.	Moffat and central part of region.	Ayrshire and S.W. part of region.
Caradoc or Bala.	Pale sandy shales and flagstones with occasional bands of grit and seams of black shale with Upper Hartfell graptolites (Lowther Shales).	Green and grey mudstones with black shales, forming the Upper Hartfell Shales and divided into: 3. Zone of *Dicellograptus anceps*, *Diplograptus truncatus*, *Climacograptus scalaris*. 2. Mudstone (unfossiliferous). 1. Zone of *Dicellograptus complanatus*, *Dictyonema moffatensis*.	Green mudstones and shales (Drummuck) with *Staurocephalus globiceps*, *Trinucleus*, *Asaphus*, *Dicellograptus anceps*, *Diplograptus truncatus*. Grey and dark flagstones and shales (Whitehouse) with *Ampyx*, *Asaphus*, *Dicellograptus complanatus*, *Diplograptus socialis*, *D. foliaceus*, *D. quadrimucronatus*, *Leptograptus flaccidus*, *Climacograptus tubuliferus*.
	Greywackes and shales passing north-eastwards into a thick group in which the Lower Hartfell black graptolitic shale loses its lithological character. The greywackes are often pebbly, and contain some thin limestone (Wrae, Winkstone) with Caradoc fossils.	Band of black shales about 50 feet thick forming the Lower Hartfell Shales and containing the following zones: 3. Zone of *Pleurograptus linearis*, with *Leptograptus flaccidus*, *Diplograptus foliaceus*, *Climacograptus tubuliferus*. 2. Zone of *Dicranograptus Clingani*, with *D. ramosus*, *Climacograptus caudatus*, *C. bicornis*, *Dicellograptus Forchhammeri*. 1. Zone of *Climacograptus Wilsoni*, with *Cryptograptus tricornis*, *Diplograptus rugosus*, *Lasiograptus Harknessi*, *Climacograptus Scharenbergi*.	Flags, shales, and grits (Ardwell) with *Dicellograptus Forchhammeri*, *Dicranograptus ramosus*, *Climacograptus caudatus*, *C. Scharenbergi*, *Cryptograptus tricornis*, *Diplograptus rugosus*, *Lasiograptus Harknessi*.
Llandeilo.	Greywackes and shales, including the Glenkiln Black Shales with their distinctive graptolites and bands of red nodular chert, with courses of red and green mudstone, massive grey and black cherts and occasional black shales containing Upper Llandeilo graptolites.	Group of grits and green shales with black and grey cherts and several bands of black graptolitic shale forming the Glenkiln Shales. The cherts contain more than 20 species of radiolaria. The black (Glenkiln) shales are marked by the occurrence of *Didymograptus superstes*, *Cœnograptus gracilis*, *Dicellograptus sextans*, *D. divaricatus*, *Diplograptus mucronatus*, and other forms.	Grits, flags, and shales (Balclatchie) with *Dicranograptus rectus*, *Glossograptus Hicksii*, *Climacograptus tricornis*, &c. Massive conglomerate with pebbles from the cherts and volcanic group below (Girvan). Shales with *Didymograptus superstes*, *Dicellograptus sextans*, *Diplograptus euglyphus*, *Clathrograptus*. Limestone (Stinchar, Craighead) with *Maclurea Logani*, *Ophileta compacta*, *Leptæna sericea*, and many other Llandeilo-Caradoc fossils. Thick conglomerate with some sandstones containing *Orthis confinis*, &c. Red and green mudstones with nodules and bands of red chert and jasper containing radiolaria.
	Slaggy diabases, tuffs, and agglomerates only seen on the crests of the anticlines where revealed by denudation.	Fine tuffs or volcanic mudstones are generally the only indications of the volcanic group in this district. But much of the material of the ordinary greywackes and shales has probably been derived from the denudation of the volcanic rocks.	Volcanic group, slaggy diabases and porphyrites with breccias and agglomerates and traversed by gabbros, serpentines, and other intrusive rocks (Ballantrae and lower part of Stinchar valley).
Arenig.	Not seen.	Not seen.	Black shales and limestones (Ballantrae, Lendalfoot) with *Phyllograptus typus*, *Tetragraptus bryonoides*, *T. quadribrachiatus*, *Didymograptus extensus*, *D. bifidus*, &c., and forms of *Dictyonema*, *Lingula*, and *Obolella*.

In the north-east of Ireland a broad belt of Silurian rocks, crossing from the south-west of Scotland, runs from the coast of Down into the heart of the counties of Roscommon and Longford. It is marked by the same graptolitic zones that occur in Scotland. The Glenkiln shales with their typical Llandeilo graptolites are found to the south of Belfast Lough, while the Hartfell shales with their Caradoc fossils have also been observed.[1] The richest fossiliferous localities among the Irish Silurian rocks are found at the Chair of Kildare, Portrane near Dublin, Pomeroy in Tyrone, and Lisbellan in Fermanagh, where small protusions of the older rocks rise as oases among the surrounding later formations. Portlock brought the northern and western localities to light, and Murchison pointed out that, while a number of the trilobites (*Trinucleus*, *Phacops*, *Calymene*, *Illænus*), as well as the simple plated *Orthidæ*, *Leptænæ*, and *Strophomenæ*, some spiral shells, and many *Orthocerata*, are specifically identical with those from the typical Caradoc and Bala beds of Shropshire and Wales, yet they are associated with peculiar forms, first discovered in Ireland, and very rare elsewhere in the British Islands. Among these distinctive fossils he cited the trilobites, *Remopleurides*, *Harpes*, *Amphion*, and *Bronteus*, with smooth forms of *Asaphus* (*Isotelus*), which, though abundant in Ireland and America, had seldom been found in Wales or England, and never on the continent.[2] In the south-east of Ireland a large tract of Silurian rocks extends through the counties of Wicklow, Wexford, and Waterford. In this area also the Llandeilo and Caradoc graptolitic zones occur. Even as far south as the southern coast-line of Waterford black shales continue the physical aspect of the Glenkiln shales, and contain some of the same graptolites. We have thus evidence that the black carbonaceous mud in which these graptolites lived spread over the sea-floor for a distance of at least 300 miles.

b. Upper Silurian.

Wales and Shropshire.—This series of rocks occurs in two very distinct lithological types in the British Islands. So great indeed is the contrast between these types, that it is only by a comparison of organic remains that the whole has been grouped together as the deposits of one geological period. In the original Shropshire region described by Murchison, and from which his type of the system was taken, the strata are comparatively flat, soft, and unaltered, consisting mainly of somewhat incoherent sandy mudstone and shale, with occasional-bands of limestone. But as these rocks are followed into North Wales, they are found to swell out into a vast series of grits and shales, so like portions of the hard altered Lower Silurian rocks that, save for the evidence of fossils, they would naturally be grouped as part of that more ancient series. In Westmoreland and Cumberland, and still farther north in the border counties of Scotland, also in the south-west of Ireland, it is the North Welsh type which prevails. This type, therefore, is really the prevalent one in Britain, extending over many hundreds of square miles, while the original Shropshire type hardly spreads beyond the border district between England and Wales.

Taking first the original tract of Siluria (W. England and E. and S.E. Wales), we find a decided unconformability separating the Lower from the Upper Silurian deposits. In some places the latter steal across the edges of the former, group after group, till they lie directly upon the Cambrian rocks. Indeed, in one district, between the Longmynd and Wenlock Edge, the base of the Upper Silurian rocks is found within a few miles to pass from the Caradoc group across to the Longmyndian rocks. It is evident, therefore, that in the Welsh region very great disturbance and extensive denudation preceded the commencement of the deposition of the Upper Silurian rocks. As Sir A. C. Ramsay has pointed out, the area of Wales, previously covered by a wide though shallow sea, was ridged up into a series of islands, round the margin of which the conglomerates at the base of the Upper Silurian series began to be laid down. This took place during a time of submergence, for these conglomeratic and sandy strata are found creeping up the slopes and even capping some of the hills, as at Bogmine, where they reach a height of 1150 feet above the sea. The subsidence probably continued during the whole of the interval occupied by the deposition of the Upper Silurian strata, which were thus piled to a depth of from 3000 to 5000 feet over the disturbed and denuded platform of Lower Silurian rocks.

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[1] W. Swanston, *Trans. Belfast Nat. Field Club*, 1876-77. Lapworth, *Ann. Mag. Nat. Hist.* iv. (1879) p. 424.

[2] 'Siluria,' p. 174. The upper portion of the Pomeroy section has yielded Llandovery graptolites, so that the strata there are partly Lower and partly Upper Silurian.

Arranged in tabular form, the subdivisions of the Upper Silurian rocks of Wales and the adjoining counties of England are in descending order as follows:—

	Base of Old Red Sandstone.	
3. Ludlow group.	Tilestones.	
	Downton Castle Sandstone, 90 feet.	
	Ledbury Shales, 270 feet.	
	Upper Ludlow Rock, 140 feet.	
	Aymestry Limestone, up to 30 or 40 feet.	
	Lower Ludlow Rock, 350 to 700 feet.	
2. Wenlock group.	Wenlock or Dudley Limestone, 300 feet	= Denbighshire Grits of North Wales.
	Wenlock Shale, up to 2300 feet	
	Woolhope or Barr Limestone and Shale, 150 feet	
1. Llandovery group.	Tarannon Shales, 1000 to 1500 feet.	
	Upper Llandovery Rocks and May Hill Sandstone, 800 feet.	
	Lower Llandovery Rocks, 600 to 1500 feet.	

1. Llandovery Group.—The most marked lithological character of this group in Britain is the occurrence of conglomerates which indicate the terrestrial disturbance and extensive denudation that followed the close of the deposition of the Lower Silurian rocks.

(*a*) *Lower Llandovery.*—In North Wales, the Bala beds, about five miles S.E. of Bala Lake, begin to be covered with grey grits, which gradually expand southwards until they attain a thickness of 1000 or even 1500 feet. These overlying rocks are well displayed near the town of Llandovery, where they contain some conglomerate bands, and where Mr. Aveline detected an unconformability between them and the Bala group below them. Elsewhere they seem to graduate downwards conformably into that group. They cover a considerable breadth of country in Cardigan and Carmarthenshire, owing to the numerous undulations into which they have been thrown, and they extend as far as Haverford West in Pembrokeshire. A marked change is now visible in the fossil contents of the rocks, as compared with those of the Lower Silurian subdivisions. Thus the familiar Lower Silurian types of trilobites become few or extinct, such as *Agnostus*, *Ampyx*, *Asaphus*, *Ogygia*, *Remopleurides*, *Trinucleus*, and their places are taken by species of *Acidaspis*, *Encrinurus*, *Phacops*, *Proëtus*, and other genera. A still more striking contrast occurs among the types of graptolites. The families of the Dicranograptidæ, Leptograptidæ, and Lasiograptidæ wholly disappear, and the forms which now take their place and distinguish the Upper Silurian rocks belong to the Monograptidæ which gradually exclude the Diplograptidæ, until before the higher parts of the system are reached they are the sole representatives of the graptolites. Four graptolitic zones have been recognised in the Llandovery group, viz. in ascending order: (1) *Diplograptus acuminatus*, (2) *Diplograptus vesiculosus*, (3) *Monograptus gregarius*, (4) *Monograptus spinigerus*. Besides these species, *Monograptus tenuis*, *M. attenuatus*, *M. Hisingeri*, *M. lobiferus*, and *Rastrites peregrinus* are common Llandovery forms. Other characteristic fossils are *Orthis elegantula*, *Stricklandinia* (*Pentamerus*) *lens*, *Meristella crassa*, and *Calymene Blumenbachii*. From the abundance of the peculiar brachiopods termed *Pentamerus* in the Lower, but still more in the Upper Llandovery rocks, these strata were formerly grouped together under the name of "Pentamerus beds." Though the same species are found in both divisions, *Pentamerus oblongus* is chiefly characteristic of the upper group and comparatively infrequent in the lower, while *Stricklandinia* (*Pentamerus*) *lens* abounds in the lower, but appears more sparingly in the upper. The genus ascends into the Wenlock and Ludlow groups, and is specially distinctive of Upper Silurian rocks.

(*b*) *Upper Llandovery and May Hill Sandstone.*—This sub-group has received the name of May Hill Sandstone from the locality in Gloucestershire where, as first shown by Murchison, it is well displayed. Sedgwick pointed out that it forms over a wide region the natural base to the Upper Silurian series, for it rests unconformably on all older rocks. It consists of grey, yellow and brown ferruginous sandstones and conglomerates, sometimes calcareous from the abundance of shells, which are apt to weather out and leave casts. Where the organisms have been most crowded together the rock even passes into a limestone (Pentamerus limestone, Norbury limestone, Hollies limestone). The lower members are usually strongly conglomeratic, the pebbles being derived, sometimes in great part, from Lower Silurian rocks. Appearing on the coast of Pembrokeshire at Marloes Bay, this sub-group ranges across South Wales until it is overlapped by the Old Red Sandstone. It emerges again in Carmarthenshire, and trends north-eastward as a narrow strip at the base of the Upper Silurian series, from a few feet to 1000 feet or more in thickness, as far as the Longmynd, where, as a marked conglomerate wrapping round that ancient Cambrian ridge, it disappears. In the course of this long tract it passes successively and unconformably over Lower Llandovery, Caradoc, Llandeilo, Cambrian, and pre-Cambrian rocks.

Among the fossils are some traces of fucoids: sponges (*Cliona*, a burrowing form like the modern *Cliona*); species of *Monograptus* (*M. Hisingeri*, *M. intermedius*, *M. crenularis*), *Rastrites* (*R. peregrinus*), *Diplograptus*, (*D. Hughesi*), *Cephalograptus* (*C. cometa*); a number of corals (*Petraia*, *Heliolites*, *Favosites*, *Halysites*, *Syringopora*, &c.); a few crinoids and the earliest known sea-urchins (*Palæchinus*); the genus *Tentaculites* is particularly abundant; a number of trilobites, of which *Phacops Stokesii*, *P. Weaveri*, *Encrinurus punctatus*, *Calymene Blumenbachii*, *Proëtus Stokesii*, and *Illænus Thomsoni* are common; numerous brachiopods, as *Atrypa hemispherica*, *A. reticularis*, *Pentamerus oblongus*, *Stricklandinia lyrata*, *S. lens*, *Leptæna transversalis*, *Orthis calligramma*, *O. elegantula*, *O. reversa*, *Strophomena compressa*, *S. pecten*, and *Lingula parallela*; lamellibranchs of the mytiloid genera *Orthonota*, *Mytilus*, and *Modiolopsis*, with forms of *Pterinea*, *Ctenodonta*, and *Lyrodesma*; gasteropods, particularly the genera *Acroculia*, *Raphistoma*, *Murchisonia*, *Pleurotomaria*, *Cyclonema*, *Holopella*; heteropods, especially the species *Bellerophon dilatatus*, *B. trilobatus*, and *B. carinatus*; and cephalopods, chiefly *Orthocerata*, with some forms of *Actinoceras*, *Cyrtoceras*, *Tretoceras*, and *Phragmoceras*, and the old species *Lituites cornu-arictis*.

(*c*) *Tarannon Shale.*—Above the Upper Llandovery beds comes a very persistent band of fine, smooth, light grey or blue slates, which has been traced from the mouth of the Conway into Carmarthenshire. These strata, termed the "paste-rock" by Sedgwick, have an extreme thickness of 1000 to 1500 feet. Poor in organic remains, their chief interest lies in the fact that the persistence of so thick a band of rock between what were supposed to be continuous and conformable formations should have been unrecognised until it was proved by the detailed mapping of the Geological Survey. The occurrence of certain species of graptolites affords a palæontological basis for placing on this horizon a considerable mass of slaty and gritty strata in Cardiganshire, and for identifying these and the typical Tarannon Shales with their probable equivalents in the Lake District and in Scotland. The following graptolitic zones in ascending order have been determined in the Tarannon rocks: (1) *Rastrites maximus*, (2) *Monograptus exiguus*, (3) *Cyrtograptus Grayæ*. Other common species are *Monograptus galaensis*, *M. priodon*, *M. riccartonensis*, and *Retiolites geinitzianus*.

2. **Wenlock Group.**—This suite of strata includes the larger part of the known Upper Silurian fauna of Britain, as it has yielded more than 160 genera and 500 species. In the typical Silurian area of Murchison, it consists of two limestone bands

(Woolhope and Wenlock), separated by a thick mass of shale (Wenlock Shale). The following sub-groups in ascending order are recognised :—

(*a*) *Woolhope Limestone.*—In the original typical Upper Silurian tract of Shropshire and the adjacent counties, the Upper Llandovery rocks are overlain by a local group of grey shales containing nodular limestone, which here and there swells out into beds having an aggregate thickness of 30 or 40, but at Malvern as much as 150 feet. These strata are well displayed in the picturesque valley of Woolhope in Herefordshire, which lies upon a worn quâ-quâ-versal dome of Upper Silurian strata, rising in the midst of the surrounding Old Red Sandstone. They are seen likewise to the north-west, at Presteign, Nash Scar, and Old Radnor in Radnorshire, and to the east and south, in the Malvern Hills (where they include a great thickness of shale below the limestone), and May Hill in Gloucestershire. Among the common fossils of these strata may be mentioned *Illænus* (*Bumastus*) *barriensis*, *Homalonotus delphinocephalus*, *Phacops caudatus*, *Encrinurus punctatus*, *Acidaspis Brightii*, *Atrypa reticularis*, *Orthis calligramma*, *Strophomena imbrex*, *S. euglypha*, *Leptæna transversalis*, *Rhynchonella borealis*, *R. Wilsoni*, *Euomphalus sculptus*, *Orthoceras annulatum.*

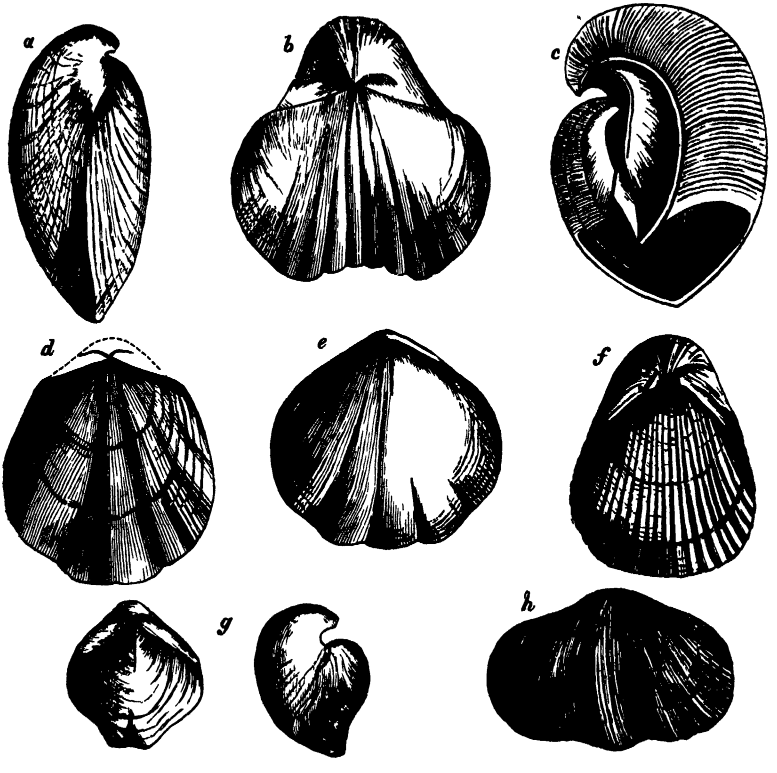

Fig. 344.—Group of Pentameri from Llandovery and Wenlock Rocks.
a, Pentamerus oblongus, Sby.; *b*, P. galeatus, Dalm.; *c*, P. Knightii, Sby.; *d*, P. oblongus, Sby.; *e*, P. rotundus, Sby. (?); *f*, P. Knightii (small specimen); *g*, P. linguifer, Sby.; *h*, P. undatus, Sby.

It is a feature of the older Palæozoic limestones to occur in a very lenticular form, swelling in some places to a great thickness and rapidly dying out, to reappear again perhaps some miles away with increased proportions. This local character is well exhibited by the Woolhope limestone. Where it disappears, the shales underneath and intercalated with it join on continuously to the overlying Wenlock shale, and no line for the Woolhope sub-group can then be satisfactorily drawn. The same discontinuity is strikingly traceable in the Wenlock limestone to be immediately referred to.

(*b*) *Wenlock Shale.*—This sub-group consists of grey and black shales, traceable from the banks of the Severn near Coalbrook Dale across Radnorshire to near Carmarthen —a distance of about 90 miles. The same strata reappear in the protrusions of Upper Silurian rocks which rise out of the Old Red Sandstone plains of Gloucestershire, Herefordshire, and Monmouthshire. In the Malvern Hills, they are estimated by Professor Phillips to reach a thickness of 640 feet, but towards the north they thicken out to more than 2000 feet. On the whole, the fossils are identical with those of the overlying limestone. The corals, however, so abundant in that rock, are here comparatively rare. The brachiopods (*Lingula, Leptæna, Orthis, Strophomena, Atrypa, Rhynchonella, Spirifer*) are generally of small size—*Orthis biloba, O. hybrida,* and the large flat *O. rustica* being characteristic.[1] Of the higher mollusca, thin-shelled forms of *Orthoceras* are specially abundant. Among the trilobites, *Encrinurus punctatus, E. variolaris, Calymene Blumenbachii, C. tuberculosa, Phacops caudatus, P. longicaudatus* are common. Distinctive species of graptolites characterise the shales of this group. At the base lies the zone of *Cyrtograptus Murchisoni,* with *Monograptus priodon, M. Halli, M. vomerinus, M. colonus* and *Retiolites geinitzianus.* Higher up comes the zone of *Cyrtograptus Linnarssoni* and still higher that of *Monograptus testis.* The most abundant Wenlock species in Britain are *M. vomerinus, M. riccartonensis,* and *M. priodon,* which last does not appear to reach the Lower Ludlow rocks.[2]

(*c*) *Wenlock Limestone.*—This is a thick-bedded, sometimes flaggy, usually more or less concretionary limestone, grey or pale pink, often highly crystalline, occurring in some places as a single massive bed, in others as two or more bands separated by grey shales, the whole forming a thickness of rock ranging from 100 to 300 feet. As its name denotes, it is typically developed along Wenlock Edge in Shropshire, where it runs as a prominent ridge for fully 20 miles; also between Aymestry and Ludlow. It likewise appears at the detached areas of Upper Silurian strata above referred to, being specially well seen near Dudley (whence it is often spoken of as the Dudley limestone), Woolhope, Malvern, May Hill, and Usk in Monmouthshire.

A distinguishing characteristic of the Wenlock limestone is the abundance and variety of its corals, of which no fewer than 24 genera and upwards of 80 species have been described. The rock seems, indeed, to have been formed in part by massive sheets and bunches of coral. Characteristic species are *Halysites catenularia, Heliolites interstinctus, H. tubulatus, Alveolites Labechei, Favosites aspera, F. fibrosa, F. gotlandica, Cœnites juniperinus, Syringopora fascicularis, Omphyma subturbinatum.* The crinoids are also specially abundant, and often beautifully preserved, *Periechocrinus moniliformis* being one of the most frequent; others are *Crotalocrinus rugosus, Cyathocrinus goniodactylus,* and *Marsupiocrinus cælatus.* Several cystideans occur, of which one is *Pseudocrinites quadrifasciatus.* More than 30 species of annelides have been found. The crustaceans include numerous trilobites, one of the most abundant being the long-lived *Calymene Blumenbachii,* which ranges from the Llandeilo flags (possibly from a still lower horizon) up to near the top of the Upper Silurian formations. It occurs abundantly at Dudley, where it received the name of the "Dudley Locust." Other common forms are *Encrinurus punctatus*, *E. variolaris*, *Phacops caudatus*, *P. Downingiæ*, *P. Stokesii*, *Illænus* (*Bumastus*) *barriensis*, *Homalonotus delphinocephalus*, and *Cheirurus bimucronatus*. One of the most remarkable features in the crustacean fauna is the first appearance of the merostomata, which are represented by *Eurypterus punctatus*, *Hemiaspis horridus*, and *Pterygotus problematicus*. The brachiopods continue to be abundant, about 20 genera and 100 species having up to this time been enumerated. Among typical species may be noted *Atrypa reticularis*, *Whitfieldia* (*Meristella*) *tumida*, *Spirifer elevatus*, *S. plicatellus*, *Rhynchonella borealis* (very common), *R. cuneata*, *R. Wilsoni*, *Orthis elegantula*, *O. hybrida*, *Strophomena rhomboidalis*, and *Pentamerus galeatus*. The lamellibranchs are abundant and are represented by species of *Avicula*, *Pterinea*, *Cardiola*, and *Cucullella*, with *Grammysia cingulata*, *Orthonota amygdalina*, and some species of *Modiolopsis* and *Ctenodonta*. The gasteropods are marked by species of *Euomphalus*, *Murchisonia*, *Holopella*, *Acroculia*, *Cyclonema*. The cephalopods are confined to five genera, *Lituites*, *Actinoceras*, *Cyrtoceras*, *Orthoceras*, and *Phragmoceras*; of these the orthoceratites are by far the most abundant both in species and individuals, *Orthoceras annulatum* being the most common form. The pteropods appear in the beautiful and abundant *Conularia Sowerbyi*, and the heteropods in the common and characteristic *Bellerophon wenlockensis*.

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[1] As an example of the small size but extraordinary abundance of brachiopods in this formation reference may be made to the fact that a cartload of the shale from Buildwas was found by careful washing to contain no fewer than 4800 specimens of one species (*Orthis biloba*), besides a much greater bulk of other brachiopods, amounting together to 10,000 specimens at least; while from seven tons weight of the shale at least 25,000 specimens of *Orthis biloba* were obtained.—Davidson and Maw, *Geol. Mag.* 1881, p. 101.

[2] Lapworth, *Ann. Mag. Nat. Hist.* v. (1880) p. 369.

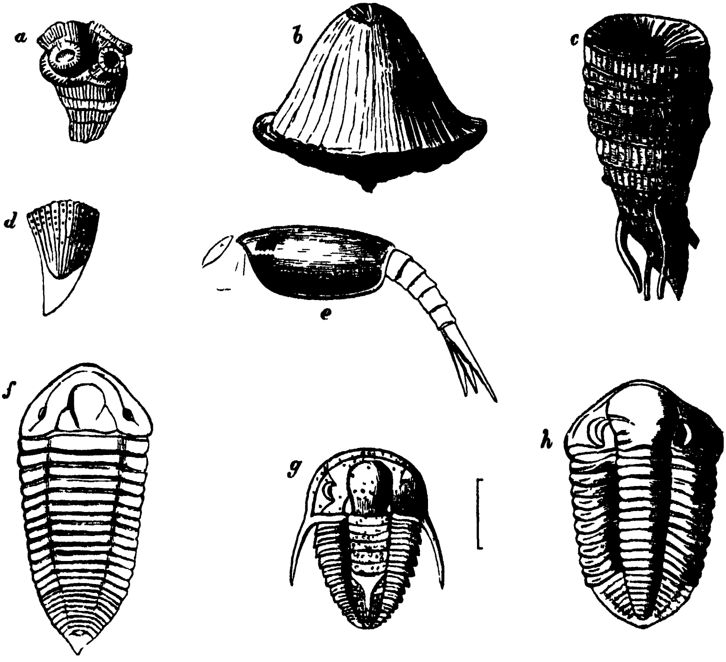

Fig. 345.—Upper Silurian Corals and Crustaceans.

a, Acervularia ananas, Linn.; *b*, Ptychophyllum patellatum, Schloth. (½); *c*, Omphyma subturbinatum, Linn. (½); *d*, Petraia bina, Lons.; *e*, Ceratiocaris papilio, Salt. (½); *f*, Homalonotus delphinocephalus, Green (½); *g*, Cyphaspis megalops, McCoy; *h*, Phacops Downingiæ, Murch.

3. Ludlow Group.—This group consists essentially of shales, with occasionally a calcareous band in the middle. It graduates downward into the Wenlock group, so that

when the Wenlock limestone disappears, the Wenlock and Ludlow shales form one continuous argillaceous formation, as they do where they stretch to the south-west through Brecon and Carmarthen. The Ludlow rocks, typically seen between Ludlow and Aymestry, appear likewise at the detached Silurian areas from Dudley to the mouth of the Severn. They were arranged by Murchison in three sub-groups—Lower Ludlow Rock, Aymestry Limestone, and Upper Ludlow Rock.

(*a*) *Lower Ludlow Rock.*—This sub-group consists of soft dark grey to pale greenish-brown or olive sandy shales, often with calcareous concretions. Much of the rock, however, presents so little fissile structure as to get the name of mudstone, weathering out into concretions which fall to angular fragments as the rock crumbles down. It becomes more sandy and flaggy towards the top. From the softness of the shales, this zone of rock has been extensively denuded, and the Wenlock limestone rises up boldly from under it. It attains a thickness of 750 feet at Malvern.

An abundant suite of fossils is contained in these shales. Eight species of star-fishes have been found, belonging to the genera *Protaster* (like the brittle-stars of the British seas), *Palæodiscus*, and *Palæocoma*. The graptolites which played so conspicuous a part in the marine fauna of Cambrian and Silurian time now appear for the last time. They are restricted entirely to the genus *Monograptus*, of which *M. Nilssoni*, *M. colonus*, *M. leintwardinensis*, *M. Salweyi*, *M. bohemicus*, *M. scanicus*, *M. priodon* (var. *ludensis*), and *M. Roemeri* are especially characteristic. The distinctive graptolitic zone of this part of the Silurian series has been named that of *Monograptus Nilssoni*, and is the last of the long series.

A few corals occur in the Lower Ludlow rock, all of species that had already appeared in the Wenlock limestone, but the conditions of deposit were evidently unfavourable for their growth. The trilobites are less numerous than in older groups; they include the venerable *Calymene Blumenbachii*; also *Phacops caudatus*, *P. constrictus*, *P. Downingiæ*, *Acidaspis coronatus*, *Cheirurus bimucronatus*, *Encrinurus punctatis*, *Lichas anglicus*, *Homalonotus delphinocephalus*, *H. Knightii*, and *Cyphaspis megalops*. But other forms of crustacean life occur in some number. As the trilobites began to wane, numerous phyllopods appeared, the genus *Ceratiocaris* being represented by nine or more species. Still more remarkable, however, was the increasing importance of the merostomatous crustaceans (*Eurypterus*, *Hemiaspis*, *Pterygotus*). Though brachiopods are not scarce, hardly any seem to be peculiar to the Lower Ludlow rock, nearly all of the known species occurring in the Wenlock group. *Rhynchonella Wilsoni*, *Spirifer exporrectus*, *S. crispus*, *S. bijugosus*, *Strophomena euglypha*, *S. rhomboidulis*, *Atrypa reticularis*, *Discina Morrisii*, *Lingula lata*, and *L. Lewisii* are not infrequent. Among the more frequently recurring species of lamellibranchs the following may be named—*Cardiola interrupta*, *C. striata*, *Ctenodonta sulcata*, *Grammysia cingulata*, *Modiolopsis gradata*, *M. Nilssoni*, *Orthonota amygdalina*, *O. rigida*, *O. semisulcata*, and a number of species of *Pterinea*. Among the gasteropods not uncommon species are *Cyclonema corallii*, *Euomphalus alatus*, *Holopella gregaria*, *Loxonema sinuosa*, and *Murchisonia Lloydii*. The old heteropod genus *Bellerophon* is still represented (*B. expansus*). The cephalopods abound, the genus *Orthoceras* being the prevalent type (*O. angulatum*, *O. annulatum*, *O. bullatum*, *O. ludense*, *O. subundulatum*, *O. tracheale*), but with species of *Exosiphonites*, *Lituites*, and *Phragmoceras*. The numbers of straight and curved cephalopods form one of the distinguishing features of the zone. At one locality, near Leintwardine in Shropshire, which has been prolific in Lower Ludlow fossils, particularly in star-fishes and eurypterid crustaceans, a fragment of the fish *Scaphaspis* (*Pteraspis*) *ludensis* was discovered in 1859. This is the earliest trace of vertebrate life yet detected in Britain. It is interesting to note that this fish does not stand low in the scale of organisation, but has affinities with our modern sturgeon.

(*b*) *Aymestry Limestone*—a dark grey, somewhat earthy, concretionary limestone in beds from 1 to 5 feet thick. Where at its thickest (from 30 to 40 feet) it forms a conspicuous feature, rising above the soft and denuded Lower Ludlow shales. Owing to the easily removable nature of some fullers'-earth on which it lies, it has here and there been dislocated by large landslips. It is still more inconstant than the Wenlock limestone. Though well developed at Aymestry in Herefordshire, it soon dies away into bands of calcareous nodules, which finally disappear, and the lower and upper divisions of the Ludlow group then come together. The organic remains at present known are for the most part identical with Wenlock forms. It is evident that the organisms which flourished so abundantly in the clear water wherein the Wenlock limestone was accumulated, continued to live outside the area of deposit of the Lower Ludlow rock, and reappeared in that area with the return of the conditions for their existence during the deposition of the Aymestry limestone. The most characteristic fossil of the latter rock is the *Pentamerus Knightii*; other common forms are *Rhynchonella Wilsoni, Lingula Lewisii, Strophomena euglypha, Atrypa reticularis, Bellerophon dilatatus, Pterinea Sowerbyi,* with many of the same shells, corals, and trilobites found in the Wenlock limestone. Indeed, as Murchison has pointed out, except in the less number of species and the occurrence of some of the shells more characteristic of the Upper Ludlow zone, there is not much palæontological distinction between the two limestones.[1]

(*c*) *Upper Ludlow Rock.*—In the original Silurian district described by Murchison, the Aymestry limestone is covered by a calcareous shelly band full of *Rhynchonella navicula,* sometimes 30 or 40 feet thick. This layer is succeeded by grey sandy shale or mudstone, often weathering into concretions, as in the Lower Ludlow zone, and assuming externally the same rusty-brown or greyish olive-green hue. Its harder beds are quarried for building stone; but the general character of the deposit, like that of the argillaceous portions of the Upper Silurian formations as a whole, in the typical district of Siluria, is soft, incoherent, and crumbling, easily decomposing once more into clay or mud, and presenting, in this respect, a contrast to the hard, fissile, and often slaty shales of the Lower Silurian series. Many of the sandstone-beds are crowded with ripple-marks, rill-marks, and annelid-trails, indicative of the shallow littoral waters in which they were deposited. One of the uppermost sandstones is termed the "Fucoid Bed," from the number of its cylindrical seaweed-like stems. It likewise contains numerous inverted pyramidal bodies, which are believed to be casts of the cavities made in the muddy sand by the rotary movement imparted by tides or currents to crinoids or seaweeds rooted and half buried in it.[2] At the top of the Upper Ludlow rock, near the town of Ludlow, a brown layer occurs, from a quarter of an inch to three or four inches in thickness, full of fragments of fish, *Pterygotus,* and shells. This layer, termed the "Ludlow Bone-bed," is the oldest from which any considerable number of vertebrate remains has been obtained. In spite of its insignificant thickness, it has been detected at numerous localities from Ludlow as far as Pyrton Passage, at the mouth of the Severn—a distance of 45 miles from north to south, and from Kington to Ledbury and Malvern—a distance of nearly 30 miles from west to east; so that it probably covers an area (now largely buried under Old Red Sandstone) not less than 1000 square miles in extent. Yet it appears never to exceed, and usually to fall short of, a thickness of 1 foot. Fish remains, however, are not confined to this horizon, but have been detected in strata above the original bone-bed at Ludlow.

A considerable suite of organic remains has been obtained from the Upper Ludlow rock, which, on the whole, are the same as those in the zones underneath. Some minute globular bodies, doubtfully referred to the sporangia of a lycopod (*Pachytheca*[3]), occur with some other plant remains (*Pachysporangium, Actinophyllum, Chondrites*—a beautiful seaweed). Corals, as might be supposed from the muddy character of the deposit, seldom occur, though Murchison mentions that the encrusting form *Favosites fibrosus* may not infrequently be found enveloping shells, *Cyclonema corallii* and *Murchisonia corallii* being, as their names imply, its favourite habitats. All the corals of the Ludlow group are also Wenlock species. Some annelides (*Serpulites longissimus*, *Cornulites serpularius*, and *Trachyderma coriaceum*) are not uncommon. The crustacea are represented in the Upper Ludlow rock by ostracods (*Beyrichia Kloedeni*, *Leperditia marginata*, *Entomis tuberosa*), phyllopods (*Ceratiocaris*, *Dictyocaris*), and more especially by eurypterids (*Eurypterus*, *Hemiaspis*, *Pterygotus*, *Slimonia*, *Stylonurus*, *Himantopterus*). The trilobites have still further waned in the Upper Ludlow rock, though *Homalonotus Knightii*, *Encrinurus punctatus*, *Phacops Downingiæ*, and a few others still occur, and even the persistent *Calymene Blumenbachii* may occasionally be found. Of the brachiopods, the most abundant forms in this group are *Lingula minima*, *L. lata*, *Discina rugata*, *Rhynchonella Wilsoni*, *Strophomena filosa*, and *Chonetes striatella*. The most characteristic lamellibranchs are *Orthonota amygdalina*, *Goniophora cymbæformis*, *Pterinea lineata*, *P. retroflexa*; some of the commonest gasteropods are *Murchisonia corallii*, *Platyschisma helicites*, and *Holopella obsoleta*. The orthoceratites are specifically identical with those of the Lower Ludlow rock, and are sometimes of large size, *Orthoceras bullatum* being specially abundant. The fish-remains consist of bones, teeth, shagreen-like scales, plates, and fin-spines. They include some plagiostomous (placoid) forms (*Thelodus*), shagreen-scales (*Sphagodus*), and some ostracosteans (*Cephalaspis* (*C. ornatus*, *C. Murchisoni*), *Auchenaspis* (*A. Salteri*), *Pteraspis* (*P. Banksii*), *Scaphaspis* (*S. ludensis*), and *Eukeraspis* (*Plectrodus*) (*E. mirabilis*). Some of the spines described under the name of *Onchus* are probably crustacean.

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[1] 'Siluria,' p. 130.

[2] *Op. cit.* p. 133.

[3] See *Q. J. Geol. Soc.* xxxviii. (1882) p. 107. Mr. Carruthers suggests that they are possibly the remains of an animal rather than a plant.

(*d*) *Tilestones, Downton Castle Stone and Ledbury Shales.*—Above the Upper Ludlow shales and mudstones lies a group of fine yellow, red, and grey micaceous sandstones from 80 to 100 feet thick which have long been quarried at Downton Castle, Herefordshire. At Ledbury these sandstones are surmounted by a group of red, purple, and grey marls, shales, and thin sandstones, having a united thickness of nearly 300 feet. Originally the whole of these flaggy upper parts of the Ludlow group were called "Tilestones" by Murchison, and, being often red in colour, were included by him as the base of the Old Red Sandstone, into which they gradually and conformably ascend. They point to a gradual change of physical conditions, which took place at the close of the Silurian period in the West of England and brought in the peculiar deposits of the Old Red Sandstone. There is every reason to believe that for a long time the marine sedimentation of Upper Silurian type continued to prevail in some areas, while the probably lacustrine type of the Old Red Sandstone had already been established in others, and that by the breaking down or submergence of the barriers between these different areas, marine and lacustrine conditions alternated in the same region. The Tilestones are the records of this curious transitional time.[1]

Vegetable remains, some of which seem to be fucoids, but most of which are probably terrestrial and lycopodiaceous, abound in the Downton sandstone and passage-beds into the Old Red Sandstone. The eurypterid genera still continue to occur, together with phyllopods (*Ceratiocaris*) and vast numbers of the ostracod *Beyrichia* (*B. Kloedeni*). Prevalent shells are *Lingula cornea* and *Platyschisma helicites*. The Ludlow fishes are also met with.

In the typical Silurian region of Shropshire and the adjacent counties, nothing can be more decided than the lithological evidence for the gradual disappearance of the Silurian sea, with its crowds of graptolites, trilobites, and brachiopods, and for the gradual introduction of those geographical conditions which brought about the deposit of the

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[1] On these passage-beds see Symonds, 'Records of the Rocks,' 1872, pp. 183-215; *Q. J. Geol. Soc.* xvi. (1860) p. 193; Roberts and Randall, *op. cit.* xix. (1863) p. 229; also the remarks made on the corresponding strata in Scotland, *postea*, pp. 764, 799.

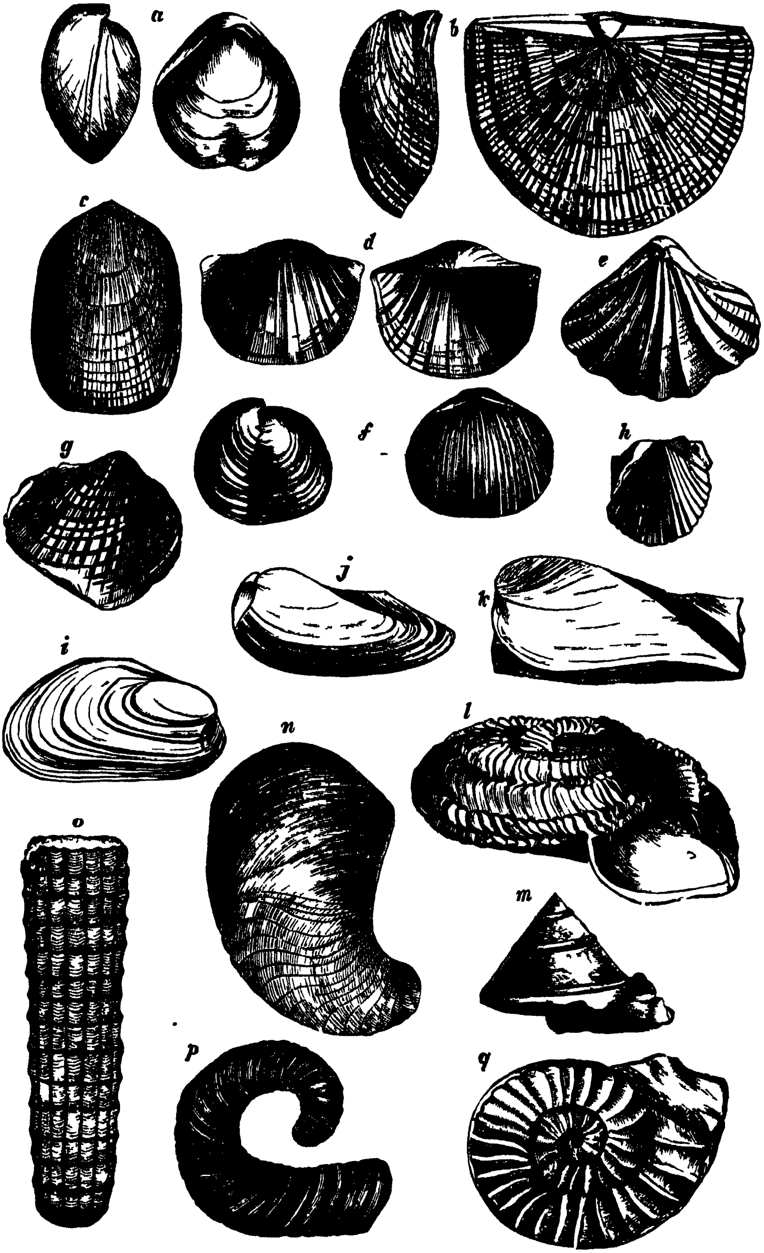

Fig 346 —Group of Upper Silurian Mollusca

a, Meristina didyma, Dalm , *b*, Strophomena antiquata, Sby , *c*, Lingula Lewisii, Sby ; *d*, Leptæna transversalis, Dalm *e*, Rhynchonella borealis, Schloth , *f*, Rhynchonella Wilsoni, Sby , *g*, Cardiola interrupta, Brod , *h*, Ambonychia acuticostata, McCoy , *i*, Modiolopsis Nilssoni, His , *j* Orthonota amygdalina, Sby , *k*, Goniophora cymbæformis, Sby , *l*, Euomphalus rugosus, Sby , *m*, Trochus cælatus, McCoy ($\frac{2}{1}$), *n*, Phragmoceras ventricosum, Sby (½), *o*, Orthoceras annulatum, Sby (½), *p*, Lituites giganteus, Sby (½), *q*, Lituites articulatus, Sby

Old Red Sandstone. The fine grey and olive-coloured muds, with their occasional zones of limestone, are succeeded by bright red clays, sandstones, cornstones, and conglomerates. The evidence from fossils is equally explicit. Up to the top of the Ludlow rocks, the abundant Silurian fauna continues in hardly diminished numbers. But as soon as the red strata begin the organic remains rapidly die out, until at last only the fish and the large eurypterid crustaceans continue to occur.

Turning now from the interesting and extremely important, though limited, area in which the original type of the Upper Silurian rocks is developed, we observe that, whether traced northwards or south-westwards, the soft mudstones and thick limestones give way to hard slates, grits, and flagstones, among which it is scarcely possible sometimes to discriminate what represents the Wenlock from what may be the equivalent of the Ludlow group. It is in Denbighshire and the adjacent counties that this change becomes most marked. The Tarannon shale above described passes into that region of North Wales, where it forms the base of the Upper Silurian formations. It is covered by a series of grits, flags, sandstones, mudstones, and shales, which in some places are at least 3000 feet thick. These are overlain by and pass laterally into hard shales, and are believed to represent the true Wenlock group, perhaps even some portion of the Ludlow rocks. The zone of *Cyrtograptus Murchisoni* which marks the lower part of the Wenlock group is found in Denbighshire, and gives a recognisable horizon. It is evident, however, that in spite of the wide extent over which these Upper Silurian rocks of North Wales are spread, and the great thickness which they attain, they do not present an adequate stratigraphical equivalent for the complete succession in the original Silurian district. Instead of passing up conformably into the base of the Old Red Sandstone, as at Ludlow, they are covered by that formation unconformably. In fact they have been upturned, crumpled, faulted, and cleaved before the deposition of those portions of the Old Red Sandstone (Upper) which lie upon them. These great physical changes took place in Denbighshire when, so far as the evidence goes, there was entire quiescence in the Shropshire district; yet the distance between the two areas was not more than about 60 miles. These subterranean movements were doubtless connected with those more widely extended upheavals that converted the floor of the Silurian sea into a series of isolated basins, in which the Old Red Sandstone was laid down (pp. 777, 799).

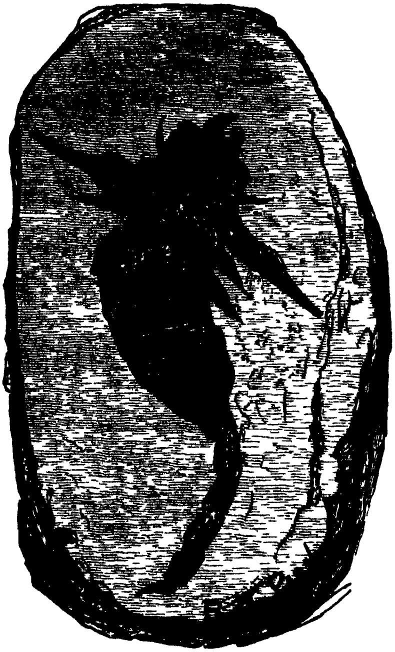

Fig. 347.—Fossil scorpion (*Palæophoneus*), Upper Silurian, Lesmahagow, Lanarkshire (about twice nat. size). Drawn by Mr. B. N. Peach.

In Westmoreland and Cumberland a vast mass of hard slates, grits, and flags, was identified by Sedgwick as of Upper Silurian age. These form the varied ranges of hills in the southern part of the Lake District, from near Shap to Duddon mouth. The following are the local subdivisions, with the conjectural equivalents in Siluria:[1]—

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[1] For papers on the Upper Silurian rocks of the Lake District see Harkness and Nichol-

Kirkby Moor Flags Hay Fell Flags (2000 feet).		Thick beds of hard sandstone, massive and concretionary or flaggy and micaceous (*Phacops Downingiæ*, *P. caudatus*, *Ceratiocaris inornatus*, *Lingula cornea*, *Orthis lunata*, *Orthonota amygdalina*, *Holopella gregaria*, *H. conica*).	=Upper Ludlow Group
Bannisdale Flags (5200 feet).		Calcareous beds (*Rhynchonella navicula* abundant) probably equivalent to the Aymestry Limestone.	=Middle Ludlow Group
		Sandstone and Shale, with star-fishes (*Protaster*).	
		Dark blue flags and grits of great thickness.	
		(*Monograptus leintwardinensis* ranges through the Bannisdale Flags and *M. colonus* and *M. Salweyi* also occur.)	=Lower Ludlow Group
Coniston Grits (upwards of 4000 feet).		Flags and greywacke generally unfossiliferous, but containing *Monograptus colonus*, *M. bohemicus*, *M. Roemeri*, *Cardiola interrupta*, *Orthoceras angulatum*, *O. primævum*, *Ceratiocaris Murchisoni*.	
Coniston Flags (2800 feet).		Dark grey coarse flags divided by Sedgwick into stages which are characterised by Mr. Marr as follows:	
		Upper Coldwell Beds (lower part of zone of *Monograptus bohemicus*) with *M. colonus*, *M. Roemeri*, *Spirorbis Lewisii*, *Ceratiocaris Murchisoni*, *Encrinurus punctatus*, *Phacops Stokesii*, *Cardiola interrupta*, *Pterinea subfalcata*, *Orthoceras primævum*, *O. dimidiatum*, *O. subundulatum*, *O. ludense*.	
		Middle Coldwell Beds (zone of *Phacops obtusicaudatus*) with *Cardiola interrupta*, *Orthoceras subannulare*, *O. angulatum*, *O. lineatum*, *O. inbricatum*.	
		Lower Coldwell Beds (zone of *Monograptus Nilssoni*).	
		Brathay Flags (zone of *Cyrtograptus Murchisoni*), fossils chiefly graptolites including *Monograptus priodon*, *M. vomerinus*, *M. cultellus*, *Retiolites geinitzianus*, *Aptychopsis*, *Cardiola interrupta*, *Orthoceras primævum*. Thickness more than 1000 feet.	Wenlock Group.
Stockdale Shales (200-450 feet).	Browgill Beds	Upper pale green and purple shales with badly preserved fossils, 67 feet.	=Llandovery Group.
		Lower pale shales (65 feet) with zones of *Monograptus crispus* and *M. turriculatus*.	
	Skelgil Beds or Graptolitic Mudstones.	Upper blue mudstones with two bands of black and blue graptolitic shale, the upper of which contains *Monograptus spinigerus*, the lower *M. Clingani*.	
		Middle blue mudstones with three bands of dark graptolitic shale, the highest being the zone of *Monograptus convolutus*, (with *M. gregarius*, *M. Clingani*, *Rastrites peregrinus* and many other graptolites), the middle being the zone of *Monograptus argenteus* (with *M. gregarius*, *M. leptotheca*, and ten other species; *Rastrites peregrinus*, and three other species; *Diplograptus tamariscus*, *D. Hughesii*, *Climacograptus normalis*, and other fossils); and the lower band being the zone of *Monograptus fimbriatus*, *M. gregarius*, *M. tenuis*, and other species; *Rastrites peregrinus*, *Diplograptus tamariscus*, *Petalograptus ovatus*, *Climacograptus normalis*.	
		Lower calcareous shales = zone of *Dimorphograptus confertus*, with *Monograptus revolutus*, *M. tenuis*, *Diplograptus vesiculosus*, &c., resting on a thin limestone with *Atrypa flexuosa*.	

In some places beneath these shales a conglomeratic band occurs that forms their base and lies unconformably on Lower Silurian strata.

In the northern part of the Lake District a great anticlinal fold takes place. The Skiddaw slates arch over and are succeeded by the base of the volcanic series above described. But before more than a small portion of that series has appeared, the whole Silurian area is overlapped unconformably by the Carboniferous Limestone. It is necessary to cross the broad plains of Cumberland and the south of Dumfriesshire before Silurian rocks are again met with. In this intervening tract, a synclinal fold must lie, for in the south of Scotland a broad tract of Upper Silurian strata is now known to form the greater part of the pastoral uplands which stretch from the Irish Sea to the North Sea. Its northern limit where it rests conformably upon and passes down into the Caradoc group, extends from a little south of Port Patrick north-eastwards to near Dunbar. The strata throughout this region have been thrown into innumerable folds which are

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son, *Quart. Journ. Geol. Soc.* xxiv. (1868) p. 296; xxxiii. (1877) p. 461. H. A. Nicholson, *op. cit.* p. 521; xxviii. (1872) p. 217, 'An Essay on the Geology of Cumberland and Westmoreland,' 1868. Nicholson and Lapworth, *Brit. Assoc.* 1875, sects. p. 78. Geol. Survey Memoirs, *Explanations of Sheet* 98, S.E. and N.E. 1872 (Aveline and Hughes). Marr, *Quart. Journ. Geol. Soc.* xxxiv. (1878) p. 871; *Geol. Mag.* 1892, p. 534; Marr and Nicholson, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 654.

often reversed. The result of this disturbance has been to compress the rocks into highly inclined positions, and to keep the same group at the surface over a great breadth of ground, so that in spite of their steep angles of dip the strata are made to occupy as much space on the map as if they were almost flat. Here and there where the anticlines are more pronounced and denudation has proceeded far enough, long boat-shaped inliers of Lower Silurian rocks have been laid bare underneath the upper series of formations. In this way the Llandeilo volcanic group can be traced by occasional exposures for some 90 miles to the north-eastward from the Ayrshire coast where it is most largely developed. By far the larger part of the Uplands is formed of rocks which, from the researches of Professor Lapworth among their graptolitic contents, are now known to be the general equivalents of the Llandovery group. Wenlock and Ludlow rocks occur on both sides of the Uplands. Towards the north-east the general lithological characters of the Upper Silurian are comparatively uniform—thick masses of greywacke and shale, with pebbly layers and well-marked bands of graptolitic black shale. This uniformity is accompanied by a corresponding monotony in the organic remains, which consist almost wholly of graptolites, confined for the most part to the zones of black shale, in which they are thickly crowded. But towards the south-west in Carrick (Ayrshire) there is a much greater diversity of sedimentation, thick masses of conglomerate, limestone and calcareous shale being conspicuous. In that district accordingly there is so marked a contrast in the abundance and variety of the organic remains, that the strata may be compared with the more fossiliferous deposits of the original and typical Silurian region. The following table shows the succession of strata which follow continuously those given in the table on p. 751.[1]

	Pentlands and northern part of region.	Central part of region.	Ayrshire and southern part of region
Ludlow Group.	Yellow and brown mudstones, shales and sandstones passing up into base of Lower Old Red Sandstones, with many Ludlow fossils (*Leptæna transversalis*, *Orthonota amygdalina*, *Platyschisma helicites*, *Orthoceras Maclareni*, *Beyrichia Kloedeni*, *Ceratiocaris*, *Dictyocaris*, *Eurypterus*, *Pterygotus*, *Slimonia*, *Stylonurus*, &c.)		Flaggy shales, grey grits, and conglomerates (Straiton), with *Beyrichia Kloedeni*, *Pterygotus*, *Ceratiocaris*, &c.
Wenlock Group	Blue, grey, and brown shales, greywackes and flaggy grits with some Wenlock fossils (*Monograptus vomerinus*, *M. colonus*, *M. priodon*, *Retiolites geinitzianus*).		Blue, grey, and yellow flagstones and shales, with *Monograptus vomerinus*, *Cardiola*, &c. Purple sandstones and calcareous bands (Penkill, Dailly), with *Cyrtograptus Grayæ*, *Retiolites geinitzianus*, and Wenlock fossils.
Llandovery Group.	Thick group of grits and greywackes, with grey shales and flagstones (Queensberry grits, Gala group) the upper portion containing *Retiolites geinitzianus*, *Monograptus priodon*, the lower portion yielding *M. exiguus*, *M. crispus*, *Protovirgularia*, *Crossopodia*, &c.	Thick group of greywackes, grits, and grey shales (Hawick group of Roxburghshire, &c., Ardwell group of Dumfriesshire and Galloway), with *Protovirgularia*, *Crossopodia*, and *Monograptidæ*.	Purple shales and mudstones, grey and green flagstones, and grits with *Monograptus exiguus*, *M. galaensis*, *Protovirgularia*, *Crossopodia*, *Cruziana*, &c. (=Stockdale shales of Lake District). Limestone (Camregan) with *Pentamerus oblongus*.

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[1] See **Lapworth**, *Quart. Journ. Geol. Soc.* xxxiv. (1878), xxxviii. (1882) ; *Geol. Mag.* 1889, pp. 20, 59 ; *Ann. Mag. Nat. Hist.* 1879, 1880.

		Pentlands and northern part of region.	Central part of region.	Ayrshire and southern part of region.
Llandovery Group (*continued*).		Greywackes, flagstones, and shales, with occasional bands of conglomerate, some of which contain fragments of rocks like those of the Highlands. Thin leaves of black shale in this group (Queensberry in part, Dalveen and Haggis-rock groups of Geological Survey) contain Birkhill graptolites.	Greywackes and shales including the black graptolitic Birkhill shales which form two bands separated by alternations of grey and green shales, and are sub-divided as follows:—	
	Upper Birkhill.		3. Zone of *Rastrites maximus*, *Monograptus turriculatus*, &c. 2. Zone of *Monograptus spinigerus*, *M. distans*, &c. 1. Zone of *Monograptus Clingani*, with *M. crenularis*, *M. Sedgwicki*, *Petalograptus cometa*.	Greywackes, shales, and quartz-conglomerates, with *Monograptus turriculatus* and other Upper Birkhill graptolites. Limestone (Woodland Point), with *Pentamerus lens*, &c.
	Lower Birkhill.		3. Zone of *Monograptus gregarius*, with *M. fimbriatus*, *M. convolutus*, *Diplograptus folium*, *Rastrites peregrinus*, &c. 2. Zone of *Diplograptus vesiculosus*, with *Monograptus cyphus*, *M. tenuis*. 1. Zone of *Diplograptus acuminatus* with *Dimorphograptus elongatus?* *Monograptus attenuatus*, *M. tenuis*.	Sandstones, shales, and conglomerates, with the graptolites of the Lower Birkhill zones. Sandstones, grits, shales, and conglomerates, with *Meristella angustifrons*, *Diplograptus acuminatus* and other Lower Birkhill graptolites. The conglomerates contain the earliest traces of fragments of rocks like those of the Highlands in this region.

Silurian rocks cover large continuous tracts in the north-east and south-east of Ireland, while at many places in the interior of the island, even to the western coast, they rise up in isolated areas from under younger formations. It is evident that, except where Cambrian and pre-Cambrian rocks appear, they spread across the whole country, though now so largely concealed by the Carboniferous formations. The Scottish type of sediments and of fossils is prolonged into Down and the other counties in the north-east and east. As already stated, the Glenkiln shales with their characteristic graptolites, traced to the south-western coast-line of Scotland, reappear in full force on the Irish shore, and strike inland along the same persistent south-easterly line. They are found as far south as the southern coast of County Waterford and as far west as the flanks of the Slieve Bernagh Mountains in County Clare. In like manner the Hartfell or Caradoc-Bala shales with their distinctive graptolites are found in County Down, and probably occur in many other districts, while the Llandovery group of Birkhill has been recognised not only in Down, but in Tyrone, Fermanagh, and other counties. Abundant evidence of contemporaneous volcanic action has been obtained from the Silurian rocks of the east of Ireland.[1] Upper Silurian rocks representing the Llandovery and Wenlock formations attain an enormous development in the west of Ireland. In the picturesque tract between Lough Mask and Killary Harbour, where they reach a thickness of more than 7000 feet, they consist of massive conglomerates, sandstones, and shales, with Llandovery and Wenlock fossils and intercalated felsites, diabases and tuffs. Again, in the Dingle promontory of County Kerry, Upper Silurian strata full of Wenlock fossils contain the most impressive proofs of contemporaneous volcanic action; agglomerates, tuffs, and volcanic blocks being intermingled with the fossiliferous strata, which are further separated by thick sheets of nodular felsitic lavas.[2]

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[1] *Quart. Journ. Geol. Soc.* xlvii. (1891) Presidential Address, p. 150, and authorities there cited.

[2] *Op. cit.* p. 159, and authorities cited. Consult on Irish Silurian rocks the Explanations to the one-inch Sheets of the Geological Survey.

Basin of the Baltic, Russia and Scandinavia.[1]—The broad hollow which, running from the mouth of the English Channel across the plains of northern Germany into the heart of Russia, divides the high grounds of the north and north-west of Europe from those of the centre and south, separates the European Silurian region into two distinct areas. In the northern of these we find the Lower and Upper Silurian formations attaining an enormous development in Britain, but rapidly diminishing in thickness towards the north-east, until in the south of Scandinavia and the Gulf of Finland, they reach only about $\frac{1}{25}$th of that depth. Along the Baltic shores, too, they have on the whole escaped so well from the dislocations, crumplings, and metamorphisms so conspicuous along the north-western European border, that to this day they remain over wide spaces nearly as horizontal and soft as at first. In the southern European area, Silurian rocks appear only here and there from amidst later formations, and almost everywhere present proofs of intense subterranean movement. Though sometimes attaining considerable thickness they are much less fossiliferous than those of the northern part of the region, except in the basin of Bohemia, where an exceedingly abundant series of Silurian organic remains has been preserved.

In Russia, Silurian rocks must occupy the whole vast breadth of territory between the Baltic and the flanks of the Ural Mountains, beyond which they spread eastward into Asia. Throughout most of this extensive area they lie in horizontal undisturbed beds, covered over and concealed from view by later formations. Along the southern margin of the Gulf of Finland, they appear at the surface as soft clays, sands, and unaltered strata, which, so far as their lithological characters go, might be supposed to be of late Tertiary date, so little have they been changed during the enormous lapse of ages since Lower Palæozoic time. The great plains bounded by the Ural chain on the east, by the uplands of Finland and Scandinavia on the north, and by the rising grounds of Germany on the south-west, have thus from a remote geological antiquity been exempted from the terrestrial corrugations that have affected so much of the rest of Europe. They have been alternately, but gently, depressed as a sea-floor, and elevated into steppes or plains. But along the flanks of the Ural Mountains, the older Palæozoic rocks have been upheaved and placed on end or at a high angle against the central portions of that chain; and, according to the observations of Murchison, Keyserling and De Verneuil, have been partially metamorphosed into chlorite-schists, mica-schists, quartzites and other crystalline rocks. To the north-west also, over a vast region in Scandinavia, they have been subjected to gigantic displacements and great regional metamorphism (p. 621).

Taking first their unaltered condition, we find them well exposed along the southern shores of the Gulf of Finland, in the Baltic provinces of Russia, where, according to F. Schmidt, they form with the Cambrian groups below them one continuous and conformable series, and are capable of arrangement as in the subjoined table:[2]—

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[1] Consult Angelin's 'Palæontologica Suecica' (1854); Kjerulf, 'Norges Geologi,' 1879 (or 'Geologie des Sudl. Norvegen' (Gurlt), 1880); Linnarsson, *Svensk. Vet. Akad.* viii. No. 2; *Zeitsch. Deutsch. Geol. Gesell.* xxv. 675; *Geol. Mag.* 1876, pp. 145, 240, 287, 379; *Geol. Föreningens Stockholm Förhandl.* 1872-74, 1877, 1879; S. Törnquist, *Kong. Vet. Akad. Förhandl.* 1874, No. 4; *Geol. Fören. Stockholm Förhandl.* 1879; Lundgren, *Neues Jahrb.* 1878, p. 699; Brogger, 'Die Silurischen Etagen 2 und 3 im Kristiania Gebiet,' 1882; F. Schmidt, *Q. J. Geol. Soc.* 1882, p. 514; J. E. Marr, *Quart. Journ. Geol. Soc.* 1882, p. 313; A. G. Nathorst, 'Sveriges Geologi,' part i. 1892, and papers cited below.

[2] *Mém. Ac. Imp. St. Pétersb.* (7) xxx. (1881) No. 1; *Q. J. Geol. S.* xxxviii. 1882, p. 514.

Upper Silurian.

Stage K. Upper Oesel Zone (50 or 60 ft. = Ludlow Group)—grey limestones and marls, yellow limestones: *Spirifer elevatus, Chonetes striatella, Beyrichia tuberculata, Pterinea retroflexa*; an abundant eurypterid fauna and fish remains (*Onchus, Pachylepis*).

„ I. Lower Oesel Zone (60 ft. = Wenlock)—chiefly dolomites with marls: *Orthoceras annulatum, Euomphalus funatus, Spirifer crispus, Orthis elegantula, Leptæna transversalis.*

„ H. Pentamerus-esthonus Zone—in the east, dolomites; in the west, grey coral limestone, with *Pentamerus esthonus* (*oblongus*), *Syringopora bifurcata, Favosites gotlandica, Halysites* (5 sp.)

„ G.
- 3. Raikull Beds (100 ft.)—coral-reefs and flagstones: *Leperditia Keyserlingii, Phacops elegans.*
- 2. Borealis Bank (40 ft.)—consisting almost entirely of agglomerated shells of *Pentamerus borealis.*
- 1. Jorden Beds (20–30 ft.)—thin calcareous flagstones and marls: *Leperditia Hisingeri, Orthis Davidsoni, Strophomena pecten, Rhynchonella affinis.*

Lower Silurian.

„ F. (1) Lyckholm and (2) Borkholm Zones (100 ft. = Middle Bala or Caradoc), contain the most abundant fauna of all the stages: *Phacops* (*Chasmops*) *macroura, Cheirurus octolobatus, Encrinurus multisegmentatus, Bellerophon bilobatus, Strophomena expansa, Orthis vespertilio, O. Actoniæ, O. insularis.*

„ E. Wesenberg Zone (30 ft. = Bala or Caradoc)—hard yellowish limestone, with marly partings: *Leptæna sericea, Strophomena deltoidea, Orthis testudinaria, Phacops Nieszkowskii, P. wesenbergensis, Encrinurus Seebachi, Cybele brevicauda.*

„ D. Jewe Zone (100 ft.), consisting of a lower or Jewe band and an upper or Kegel band: *Cheirurus pseudohemicranium, Hemicosmites extraneus, Lichas deflexa, L. illænoides, Chasmops bucculenta, Strophomena Asmusii.*

„ C.
- 3. Itfer Beds (20–30 ft.)—hard limestone with siliceous concretions; fauna nearly same as in C. 2, but with some peculiar trilobites, and some forms belonging to Stage D.
- 2. Kuckers Shale (Brandschiefer), consisting of bituminous marls and limestones (30–50 ft.): *Phacops exilis, P.* (*Chasmops*) *Odini, Cheirurus spinulosus, Pleurotomaria elliptica, Porambonites teretior, Orthis lynx, Echinosphærites aurantium.*
- 1. Echinosphærite Limestone, &c. (20–50 ft. = uppermost Orthoceratite Limestone of Sweden)—*Echinosphærites aurantium*, and *Orthoceras regulare* are the most characteristic fossils, with numerous trilobites.

„ B.
- 3. Orthoceratite (Vaginaten-) Limestone (3–20 ft. = Orthoceras limestone of Scandinavia)—hard grey limestone crowded with *Orthoceras commune* and *O. vaginatum*; also *Phacops sclerops, Cheirurus ornatus, Asaphus heros, Ampyx nasutus*, &c.
- 2. Glauconite Limestone (12–40 ft.)—*Megalaspis planilimbata, Cheirurus clavifrons, Asaphus expansus, Porambonites reticulatus, Orthis parva.*
- 1. Glauconite Sand (Greensand), lying directly on the Cambrian Dictyonema shale (1–10 ft. = Ceratopyge Stage of Scandinavia)—*Obolus siluricus, Siphonotreta, Lingula*; "conodonts" of Pander.

In Scandinavia the following general order of succession has been established:—

Upper Silurian.
- Limestones and marls (50–60 ft. in Gothland) with Ludlow fossils.
- Limestones and shales (150 ft. in Gothland) with Wenlock fossils (*Monograptus ludensis, M. colonus, Retiolites geinitzianus*).
- Marls and shales (with Llandovery forms) apparently unconformable on all older rocks.

Lower Silurian.

- Brachiopod shales (*Trinucleus, Staurocephalus*).
- Trinucleus shales and limestones.
- Middle graptolite shales (Llandeilo species of *Didymograptus, Diplograptus, Climacograptus*, and other genera) which pass laterally into limestone, and are in different districts represented by the Chasmops limestone.
- Lower graptolite shales (Arenig species of *Phyllograptus, Dichograptus, Didymograptus*, and other genera) passing into the Orthoceras limestone, which is recognisable over a large part of southern Scandinavia.
- Ceratopyge limestone (*Dicellocephalus, Agnostus, Niobe, Amphion, Obolus*) and other fossils like those found at the base of the Arenig and in the Tremadoc group.

In Scania, the Silurian series has been subdivided into graptolitic zones as in the subjoined table:[1]—

Upper Silurian.

- A. Upper Group—Cardiola shales, with limestone and sandstone.
- B. Middle Group, with the following zones in descending order: (*a*) *Cyrtograptus Carruthersi;* (*b*) *C. rigidus;* (*c*) *C. Murchisoni;* (*d*) *Monograptus riccartonensis;* (*e*) *Cyrtog. Lapworthii;* (*f*) *C.* (?) *spiralis;* (*g*) *C. Grayæ.*
- C. Lower Group, composed of the following zones in descending order: (*a*) *Monograptus cometa;* (*b*) Grey unfossiliferous shales; (*c*) *Cephalograptus cometa;* (*d*) *Mon. leptotheca;* (*e*) *M. gregarius;* (*f*) *M. cyphus.*

Lower Silurian.

- D. Upper Group, composed of the following zones in descending order: (*a*) *Diplograptus*, sp.; (*b*) *Phacops mucronata;* (*c*) *Staurocephalus clavifrons;* (*d*) Unfossiliferous marly shales; (*e*) *Niobe lata;* (*f*) Unfossiliferous shales; (*g*) *Diplograptus quadrimucronatus;* (*h*) *Trinucleus*, sp.; (*i*) *Calymene dilatata;* (*k*) Unfossiliferous shales.
- E. Middle Group—Graptolite shales, with zones of (*a*) *Climacograptus rugosus;* (*b*) *C. styloidens;* (*c*) Black unfossiliferous shales; (*d*) Limestone band, with *Ogygia*, sp.; (*e*) *Dicranograptus Clingani;* (*f*) *Climacograptus Vasæ;* (*g*) Unfossiliferous shales; (*h*) *Cœnograptus gracilis;* (*i*) Thin apatitic band: (*k*) *Diplograptus putillus;* (*l*) *Glossograptus;* (*m*) *Gymnograptus Linnarssoni;* (*n*) *Glossograptus;* (*o*) *Didymograptus geminus* (*Murchisoni*).
- F. Lower Group, composed of the zones of (*a*) *Phyllograptus*, sp.; (*b*) Orthoceras limestone; (*c*) Tetragraptus shales (lower graptolite shales); (*d*) Ceratopyge limestone.

The island of Gothland has long been celebrated for its development of Upper Silurian rocks. According to Lindstrom[2] the following subdivisions are there traceable:—

Ludlow.

- H. Cephalopoda and Stromatopora-Limestone (20–30 feet) with *Phragmoceras, Ascoceras, Glossoceras.*
- G. Megalomus-Limestone (8–12 feet), with *Megalomus Gotlandicus, Trimerella.*
- F. Crinoidal and Coral conglomerate (20 feet), a limestone made up of stems of crinoids, corals, and other fossils. Among the crinoids are species of *Crotalocrinus, Enallocrinus, Barrandeocrinus, Cyathocrinus*; there occur also *Spirifer Schmidti*, *Pentamerus conchidium.* This band lies somewhere about the horizon of the Aymestry Limestone.
- E. Pterygotus-clay or marl (1–2 feet) with abundant fragments of *Pterygotus osiliensis*, also *Phasganocaris, Strophomena, Eatonia, Conularia*, &c.

Wenlock.

- D. Limestone, oolite and marly bands (50 feet) with numerous lamellibranchs; species of *Pterinea, Aviculopecten*, and *Grammysia*, also *Orthis basalis, O. biforata*, and *Atrypa Angelini, Lichas, Cyclonema delicatulum*, &c.
- C. Younger marly shales and sandstone (100 feet), with a large and varied assemblage of fossils like those of the Wenlock Shale (*Phacops Downingiæ, P. vulgaris, Homalonotus Knighti, Strophomena euglypha, Orthis biloba, Strophomena Walmstedti, Rhynchonella Wilsoni, Orthoceras annulatum, O. gregarium, Monograptus ludensis, M. colonus, Retiolites geinitzianus*, &c.

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[1] S. A. Tullberg, 'Skanes Graptoliter,' *Sverig. Geol. Undersökn.* ser. c. No. 50, 1882-83.

[2] *Neues Jahrb.* 1888, i. p. 147, and F. Schmidt, *op. cit.* 1890, ii. p. 249. Murchison, *Quart. Journ. Geol. Soc.* 1847.

Llandovery.	B. Stricklandinia-marl (8 feet) with *Heliolites*, *Plasmopora*, *Halysites*, *Bronteus platyactin*, *Calymene papillosa*, *C. frontosa*, *Orthis Davidsoni*, *O. Loveni*, and especially the abundant *Stricklandinia lyrata*.
	A. Older red marly shales (thickness unknown and not seen in place) with some 40 species of fossils, among which are *Favosites gotlandica*, *F. Forbesi*, *Halysites*, *Plasmopora*, *Arachnophyllum diffluens*, &c.

In the Christiania district, according to Kjerulf, the following subdivisions can be established:—

Upper.	Stage 8.	γ. Compact grey, often bituminous limestone, with abundant *Orthoceras cochleatum* and *Chonetes striatella*.
		β. Grey, somewhat bituminous limestone, with shales and clays.
		α. Fissile green or grey marly shales containing the last graptolites. This and the two overlying members have a united depth of 835 Norwegian feet at Ringerige.
	Stages 6 & 7.	Coral limestone and Pentamerus limestone.
Lower.	Stage 5.	Calcareous sandstone, with *Rhynchonella diodonta* and shales, 150 to 370 feet.
	,, 4.	Shales and marls, with nodules and short beds of cement-stone (*Trinucleus*, *Chasmops*), 700 feet.
	,, 3.	Graptolite shales, Limestone in two or more bands (Orthoceras-, Asaphus-, Megalaspis-limestone), 250 feet in places, resting upon the alum-shales of the Primordial zone.[1]

In Easter and Wester Gothland patches of Silurian strata are met with preserved in horizontal sheets under an overlying capping of diabase. But when the rocks are traced into the western parts of Norway and through the central regions where the boundaries of Norway and Sweden meet, they present a remarkably different development from that just described. According to the researches of Kjerulf, Dahll, Tornebohm, Brögger, and Reusch, vast masses of quartzite, mica-slate, gneiss, hornblende-schist, clay-slate, and other crystalline rocks can be seen reposing upon recognisable Silurian strata in numerous natural sections. Not improbably these Scandinavian metamorphic rocks, like those occupying a similar position in Scotland, will be found to include portions of different pre-Cambrian systems which, together with the Cambrian and Silurian strata, have been subjected to such great disturbance as to have had a new crystalline structure superinduced upon them. Enormous displacements and lateral thrusts have driven the crystalline rocks over the fossiliferous strata, as in Scotland, but the details of this structure, which has been recognised by Törnebohm, have still to be worked out. As regards the date of these great earth-movements and metamorphism, it is important to remember that, as already stated (p. 712), Upper Silurian fossils have been found by Reusch at Bergen in the crystalline schists themselves, as well as in the limestones intercalated in and underlying them.[2]

Western Europe.—The researches principally of Gosselet and Malaise have demonstrated that a considerable part of the strata grouped by Dumont in his "Terrain Rhénan," and generally supposed to be of Devonian age, must be relegated to the

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[1] Professor Brogger has further subdivided Stage 3 as follows, in ascending order: *3a*, (α) Shales and limestones with *Symphysurus incipiens*, (β) Ceratopyge shales, (γ) Ceratopyge limestone; *3b*, Phyllograptus shales; *3c*, (α) Megalaspis limestone, (β) Expansus-shales, (γ) Orthoceras limestone, the whole stage having a thickness of about 47 metres in the Christiania district.—'Die Sil. Etagen,' p. 28.

[2] See Dahll, *Förh. Vedensk-Selskab.* Christiania, 1867. Kjerulf, 'Geologie des Süd. u. Mit. Norwegen,' 1880. Törnebohm, *Bihang K. Svensk. vet. Akad. Handl.* i. No. 12 (1873); *Geol. För. Stockholm Förhand.* vi. (1883) p. 274; xiii. (1891) p. 37; xiv. (1892) p. 27; *Nature*, xxxviii. (1888) p. 127. Brogger, 'Die Silurischen Etagen 2 und 3 im Kristianiagebiet,' 1882, p. 352. Pettersen, *Tromsö Museums Aarsheft*, vi. (1883) p. 87. F. Svenonius, *Neues Jahrb.* 1882 (i.) p. 181. Nathorst, 'Sveriges Geologi,' p. 141.

Silurian series.[1] Though almost concealed by younger formations, the Silurian rocks that are laid bare at the bottom of the valleys of the Ardennes can be paralleled in a general way as under :—

Upper Silurian.	Ludlow.	Equivalents of the Ludlow rocks seen in the valley of the Fuette between Fosse and Malonne, containing *Monograptus colonus*, *M. Nilssoni*, *Retiolites geinitzianus*, *Orthoceras*, *Cardiola interrupta*, &c.
	Wenlock.	Brown sandy shales of Naninne, with *Cyrtograptus Murchisoni*, *Monograptus bohemicus*, *M. Nilssoni*, *M. priodon*, *M. vomerinus*, *Retiolites geinitzianus*, *Cardiola interrupta*, *Orthoceras*, &c.
	Llandovery.	Quartzites and sandstones of Grand-Manil, with *Monograptus bohemicus*, *M. galaensis* ?, *M. priodon*, *M. proteus*, *M. subconicus*. Shales overlying the eurites of Grand-Manil, and containing *Climacograptus normalis*, *C. rectangularis*, *Dimorphograptus elongatus*, *D. Swanstoni*, *Diplograptus modestus*, *Monograptus gregarius*, *M. leptotheca*, *M. tenuis*.
Lower Silurian.	Caradoc.	*Schistes de Gembloux*; pyritous black and greenish shales, which at Grand-Manil, in the valley of the Orneau, have yielded *Calymene incerta*, *Trinucleus setiformis*, *Illænus Bowmanni*, *Bellerophon bilobatus*, *Strophomena rhomboidalis*, *Orthis testudinaria*, *O. vespertilio*, *O. calligramma*, *O. Actoniæ*, *Climacograptus caudatus*, *C. styloïdeus*, *C. tubuliferus*.
		The horizon of the Llandeilo rocks is doubtfully represented at Sart-Bernard.
	Arenig.	Graptolitic shales, with *Climacograptus antennarius*, *C. Scharenbergi*, *Dichograptus octobrachiatus*, *Didymograptus Murchisoni*, *D. nanus*, *Diplograptus foliaceus*, *D. tricornis*, *Phyllograptus angustifolius*, *P. typus*, *Tetragraptus bryonoides*, &c.
		Upper Cambrian horizons are represented at Spa and elsewhere by *Dictyonema sociale*.

The Silurian rocks of Belgium comprise several contemporaneously erupted masses of porphyrite and of diabase, as well as beds of porphyroid, arkose, and eurite.

Silurian rocks have been detected in many parts of the old Palæozoic ridge of the north-west of France. According to De Tromelin and Lebesconte,[2] the order of succession in Ille-et-Vilaine is as under :—

Upper Silurian.	Wenlock.	White limestone of Erbray (*Calymene Blumenbachii*, *Harpes venulosus*). Ampelitic (carbonaceous) limestone of Briasse (*Monograptus priodon*, *M. Hisingeri*, *M. colonus*, *M. vomerinus*, *M. jaculum*). Sandy and ferruginous nodules of Martigné-Ferchaud, Thourie, &c. (*Cardiola interrupta*, *Monograptus priodon*).
	Llandovery.	Ampelitic (carbonaceous) shales of Poligné (*Monograptus crassus*, *M. Halli*, *M. priodon*, *M. jaculum*, *M. convolutus*, *M. continens*, *Diplograptus palmeus*, *Cephalograptus folium*, *Retiolites geinitzianus*). Phtanites of Anjou (*Monograptus convolutus*, *M. crenularis*, *M. lobiferus*, *M. sublobiferus*, *M. Sedgwicki*, *M. cyphus*, *M. crispus*, *M. Clingani*, *Cephalograptus folium*, *Diplograptus Hughesi*, *Rastrites peregrinus*, *R. Linnæi*).

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[1] Gosselet, 'Esquisse Géologique du Nord de la France,' p. 34. 'L'Ardenne,' *Mém. Carte Géol. France* (1888) p. 137. Mourlon, 'Géol. de la Belgique,' p. 40 ; Malaise, *Mém. Couronn. Acad. Roy. Belgique*, 1873 ; *Bull. Acad. Roy. Belg.* xx. (1890) p. 440. C. Barrois, *Ann. Soc. Géol. Nord*, xx. (1892) p. 75 ; in this work references are given to the literature of French Silurian geology.

[2] De Tromelin and Lebesconte, *Bull. Soc. Géol. France* (1876), p. 585 ; *Assoc. Franç.* (1875) ; *Bull. Soc. Linn. Normandie* (1877), p. 5. See also Dalimier, 'Stratigraphie des Terrains primaires dans la presqu'île de Cotentin,' Paris (1861) ; *Bull. Soc. Géol. France* (1862), p. 907 ; De Lapparent, *Bull. Soc. Géol. France* (1877), p. 569 ; Barrois, *Ann. Soc. Géol. Nord*, iv. vii. and the memoirs cited below.

Lower Silurian.	Llandeilo and Bala.	Slates of Riadan (*Trinucleus*).
		Sandstones (May, Thourie, Bas-Pont, Saint-Germain de la Bouexière, &c.), containing *Trinucleus Goldfussi*, *Calymene Bayani*, *Orthis redux*, *O. budleighensis*, *O. pulvinata*, *O. valpyana*, *O. Berthosi*, *Nucleospira Vicaryi*, *Lingula Morierei*, *Pseudarca typa*, *Diplograptus foliaceus*, *D. angustifolius*.
		Slates of La Couyère (*Orthis Berthosi*).
		Nodular shales of Guichen, &c. (*Calymene Tristani*, *Placoparia Tourneminei*, *Acidaspis Buchii*).
		Slates of Angers (*Ogygia Desmaresti*, *Didymograptus Murchisoni*, *D. euodus*, *D. nanus*, *D. furcillatus*).
		Shales of Laillé and Sion (*Placoparia Zippei*, *Hyolithes cinctus*).
	Arenig.	Armorican sandstone (Grès Armoricain), containing *Asaphus armoricanus*, *Lingula Lesueuri*, *L. Hawkeii*, *L. Salteri*, *Dinobolus Brimonti*, *Lyrodesma armoricana*, annelides.
		Red shales and conglomerates without fossils.

In Normandy, where the first French graptolites were found, some of the species characteristic of the uppermost groups of Brittany have been obtained. Silurian fossils have also been detected southwards in Maine and Anjou, and still more abundantly from the ridge of old rocks which forms the high grounds of Languedoc where the following section has been determined.[1]

Shales and ampelitic orthoceratite limestones (200 metres) with *Cardiola interrupta*, *Monograptus priodon*, *M. bohemicus*, *M. colonus*, *M. Roemeri*, *M. Nilssoni*. This zone evidently corresponds with that of the English Wenlock group.

Alternations of shales and white cystidean limestones.

Shales with *Orthis Actoniæ*.

Green shales with concretions (gâteaux) formed around large trilobites, *Asaphus Fourneti*, *Illænus Lebescontei*, *Didymograptus euodus*. These strata are probably of Llandeilo age.

Sandstone and grit like the Grès Armoricain, about 50 metres thick, containing *Cruziana*, *Vexillum*, *Lingula Lesueuri*, *Dinobolus Brimonti*.

Shales with calcareous nodules (150 metres) containing *Bellerophon Oehlerti*, *Agnostus*, *Calymene*, *Illænus*, *Megalaspis*, *Didymograptus balticus*, *D. pennatulus*, *D. nitidus*, *D. bifidus*, *D. indentus*, *Tetragraptus serra*, *T. quadribrachiatus*. These strata and the overlying sandstone represent the British Arenig rocks.

Recent researches in the Pyrenees have revealed a great development of fossiliferous rocks which from their graptolites may be paralleled with the English and Scottish Tarannon sub-group.[2] Three zones with *Monograptus vomerinus*, *M. Becki*, and *M. crassus* are well developed, and are compared by Dr. Barrois with the British zones of *Rastrites maximus*, *Monograptus exiguus* and *Cyrtograptus Grayæ* respectively. The same observer remarks that these graptolitic faunas of the Pyrenees present more resemblance with others found in the south of Europe than with those in the original typical regions of Britain and Scandinavia. The specific types are generally the same as those of Bohemia.[3] Silurian rocks have been recognised at various points on the Spanish tableland, a lower quartzite, with *Cruziana*, *Lingula*, &c., being surmounted by shales containing *Calymene Tristani*, &c. Graptolite-bearing schists occur in the province of Minho in the west of Portugal.[4]

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[1] Rouville, 'Monographie Géol. de Cabrières, Herault' (1887). Bergeron, 'Étude Géol. du Massif ancien au sud du Plateau Central' (1889). Barrois, *Ann. Soc. Géol. Nord*, xx. (1892) p. 85. F. Frech, *Zeitsch. Deutsch. Geol. Ges.* (1887) p. 360.

[2] Caralp, 'Etudes géol. sur les hauts Massifs des Pyrénées centrales,' Toulouse, 1888, p. 453.

[3] Barrois, *Ann. Soc. Géol. Nord* (1892), p. 127. On the Silurian rocks of the Asturias see Barrois, *Mém. Soc. Géol. Nord*, 1882.

[4] J. F. N. Delgado, *Comm. Trabal. Geol. Portugal*, II. fasc. ii. (1892).

Upper Silurian.	3rd Fauna.	Stage H.[3]	Shales with coaly layers and beds of quartzite (*Phacops fecundus*, *Tentaculites elegans*), with species of *Leptæna*, *Orthoceras*, *Lituites*, *Goniatites*, &c.	850 ft.
		,, G.	Argillaceous limestones with chert, shales, and calcareous nodules Numerous trilobites of the genera *Dalmanites*, *Bronteus*, *Phacops*, *Proëtus*, *Harpes*, and *Calymene*; *Atrypa reticularis*, *Pentamerus linguifer*.	1000 ,,
		,, F.	Pale and dark limestone with chert. *Harpes*, *Lichas*, *Phacops*, *Atrypa reticularis*, *Pentamerus galeatus*, *Favosites gotlandica*, *F. fibrosa*, *Tentaculites*.	
		,, E.	Shales with calcareous nodules, and shales resting on sheets of igneous rock (300 ft.), lying with a slight unconformability on the group below A very rich Upper Silurian fauna, abundant cephalopods, trilobites, &c.; *Halysites catenularia*, graptolites in many species, such as are found in the Birkhill group of Britain.	450–900 ,,
Lower Silurian.	2nd Fauna.	,, D.	Yellow, grey, and black shales, with quartzite and conglomerate at base, divided by Barrande into five bands numbered D*d*1 to D*d*5, the first being further separated into three members D*d*1 α, β, and γ. D*d*1 α and β may perhaps be paralleled with the Welsh Tremadoc group, D*d*1 γ with the Arenig rocks, D*d* 2, 3, 4, and 5 with the Bala-Caradoc rocks Abundant trilobites of genera *Trinucleus*, *Ogygia*, *Asaphus*, *Illænus*, *Remopleurides*, &c.	3000 ft.
Cambrian.	Primordial Fauna.	,, C.	Shales, sometimes with porphyries and conglomerates *Paradoxides*, *Ellipsocephalus*, *Agnostus*, *Arionellus*, and other genera of trilobites referred to above (*ante*, p. 723).	300 ,,
		,, B.	Grits, shales, and conglomerates.	
Pre-Cambrian.		,, A.	Green schists, grits, breccias, tuffs, and hornstones resting on gneiss.	

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[1] Marr, *Quart. Journ. Geol. Soc.* 1880, p. 603.

[2] See Barrande's magnificent work, 'Système Silurien de la Bohème.' F. Katzer, 'Geologie von Böhmen,' 1892, p. 791. J. E. Marr, *Quart. Journ. Geol. Soc.* 1880, p. 591.

[3] Stages F, G, H are classed as Devonian by Kayser and other German geologists. (Kayser, *Zeitsch. Deutsch. Geol. Ges.* xxix. (1877) pp. 207, 629, notices the occurrence of Bohemian Upper Silurian fossils in the Rhenish Lower Devonian rocks.) Barrande defended his classification: *Verh. K. Geol. Reichs.* 1878, p. 200.

Small though the area of the Silurian basin of Bohemia is (for it measures only 100 miles in extreme length by 44 miles in its greatest breadth), it has proved extraordinarily rich in organic remains. Barrande has named and described several thousand species from that basin alone, the greater number being peculiar to it. Some aspects of its organic facies are truly remarkable. One of these is the extraordinary variety and abundance of its straight and curved cephalopods, of which 18 genera and two sub-genera, comprising in all no fewer than 1127 distinct species, were determined by Barrande. The genus *Orthoceras* alone contained in his census 554 species, and *Cyrtoceras* had 330.[1] Of the trilobites, which appear in great numbers and in every stage of growth, as many as 42 distinct genera were noted, comprising 350 species; the most prolific genus being *Bronteus*, which included 46 species entirely confined to the *3rd* fauna or Upper Silurian. *Acidaspis* had 40 species, of which six occur in the *2nd* and 34 in the *3rd* fauna. *Proëtus* also numbered 40 species, which all belong to the *3rd* fauna, save two found in the *2nd*. Other less prolific but still abundant genera are *Dalmanites*, *Phacops*, and *Illænus*. The *2nd* fauna, or Lower Silurian series, was found by Barrande to contain in all 32 genera and 127 species of trilobites; while the *3rd* fauna, or Upper Silurian series, contained 17 genera and 205 species, so that generic types are more abundant in the earlier and specific varieties in the later rocks.[2]

Reference may be made here to the famous doctrine of "Colonies" propounded and ably defended by the illustrious Barrande. Drawing his facts from the Bohemian basin he believed that while the Silurian strata of that region presented a normal succession of organic remains, there were nevertheless exceptional bands, which containing the fossils of a higher zone, were yet included on different horizons among inferior portions of the series. He termed these precursory bands "colonies," and defined the phenomena as consisting in the partial co-existence of two general faunas, which, considered as a whole, were nevertheless successive. He supposed that, during the later stages of his second Silurian fauna in Bohemia, the first phases of the third fauna had already appeared, and attained some degree of development, in a neighbouring but yet unknown region. At intervals, corresponding doubtless to geographical changes, such as movements of subsidence or elevation, volcanic eruptions, &c., communication was opened between that outer region and the basin of Bohemia. During these intervals, a greater or less number of immigrants succeeded in making their way into the Bohemian area, but as the conditions for their prolonged continuance there were not yet favourable, they soon died out, and the normal fauna of the region resumed its occupancy. The deposits formed during these partial interruptions, notably graptolitic schists and calcareous bands, accompanied by igneous sheets, contain, besides the invading species, remains of some of the indigenous forms. Eventually, however, on the final extinction of the second fauna, and, we may suppose, on the ultimate demolition of the physical barriers hitherto only occasionally and temporarily broken, the third fauna, which had already sent successive colonies into the Bohemian area, now swarmed into it, and peopled it till the close of the Silurian period.[3]

The general verdict of palæontologists has been adverse to this original and ingenious doctrine. The apparent intercalation of younger zones in older groups of rock has been accounted for by such infoldings of strata as have already been described in this volume and by the effects of faults. It has been shown that not only are the zones repeated, but that when they reappear they bring with them their minute palæontological subdivisions and their peculiar lithological characters.[4]

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[1] 'Syst. Silur.' ii. suppt. p. 266, 1877.

[2] *Op. cit.* i. suppt. "Trilobites," 1871.

[3] The doctrine of colonies is developed in the 'Système Silurien du Centre de la Bohème,' 1852, i. p. 73; 'Colonies dans le Bassin Silurien de la Bohème,' in *Bull. Soc. Géol. France* (2nd ser.) xvii. (1859) p. 602; 'Défense des Colonies,' Prague, i. (1861), ii. (1862), iii. (1865), iv. (1870), v. (1881).

[4] See J. E. Marr, *Q. J. Geol. Soc.* 1880, p. 605; 1882, p. 313.

Silurian rocks appear in a few detached areas in Germany, but the only comparatively large tract of them occurs in Thuringia and the Fichtelgebirge. They present a great contrast to those of Bohemia in their comparatively unfossiliferous character, and the absence of any one continuous succession of the whole Silurian system. In the Thuringer Wald, a series of fucoidal-slates (perhaps Cambrian) passes up into slates, greywackes, &c., with *Lingula*, *Discina*, *Calymene*, numerous graptolites and other fossils. These strata (from 1600 to 2000 feet thick) may represent the Lower Silurian groups. They are covered by some graptolitic alum-slates, shales, flinty slates, and limestones (*Favosites gotlandica*, *Cardiola interrupta*, *Tentaculites acuarius*, &c.), which no doubt represent the Upper Silurian groups, and pass into the base of the Devonian system.[1] The graptolites include many species found in the Stockdale shales of the Lake District, so that the Llandovery group is well represented in this part of the continent.[2] Among the Harz mountains certain greywackes and shales containing land-plants (lycopods, &c.), trilobites (*Dalmanites*, &c.), graptolites, &c., are regarded as of intermediate age between true Upper Silurian and Lower Devonian rocks.[3]

Among the Alps, the band of ancient sedimentary rocks, which, flanking the crystalline masses of the central chain, has been termed the "greywacke zone," has in recent years been ascertained to contain representatives of the Silurian, Devonian, Carboniferous, and Permian systems.[4] In the eastern Alps, a belt of clay-slate and greywacke, with limestone, dolomite, magnesite, ankerite, and siderite runs from Kitzbuhel in the Tyrol as far as the south end of the Vienna basin. About twenty species of fossils (*Orthoceras*, *Atrypa*, *Cardiola*, &c.) found at Dienten, near Werfen, belong apparently to the substage *e*2 of Barrande's Stage E. In this band, the strata have been changed into crystalline schists (p. 624). As the fossils are Upper Silurian, a large part of the adjacent unfossiliferous schistose rocks may represent older parts of the Silurian system; but no Lower Silurian fossils have yet been found in them in the northern Alps.

In the southern Alps (Carinthia), above the older Palæozoic masses which have not yet yielded fossils, the following subdivisions have been given by Stache in descending order:—

Limestones (1000 to 1500 feet) with Silurian forms of *Pentamerus*, *Spirifer*, *Rhynchonella* and *Atrypa*, and Silurian and Devonian corals = Stages F, G, H, of Barrande.

Dark clay-slates and sandstones with plant-remains, yellow and red crinoid-shales = Stage F, in parts Onondago group (?).

Limestone with orthoceratites, gasteropods, lamellibranchs, trilobites (Kokberg). About 100 species occur in the lower or dark Orthoceras limestone. These rocks appear to represent Stage E of Bohemia, and the Ludlow and Wenlock groups of England.

Graptolite-schists with *Diplograptus folium*, *D. pristis*, &c. = Stage D and base of E (Tarannon group).

Greywacke-slate and sandstone (*Strophomena grandis*, *Orthis*) = upper part of Stage D; perhaps Bala beds.[5]

In the southern half of Sardinia, Silurian rocks (in part, at least, Upper) have been divided into three zones, the lowest of which contains important metalliferous lodes.[1] Among these rocks Meneghini recognises two chief graptolitic horizons, one probably representing the Tarannon sub-group (with *Monograptus antennularius*, comp. *Becki*, *M. Gonii*, comp. *continens*, *M. hemipristis*, comp. *jaculum*) the other (with *M. colonus*, *M. Lamarmoræ*, *M. multuliferus*, comp. *vomerinus*) answering to the Wenlock group.

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[1] Richter, *Zeitsch. Deutsch. Geol. Gesell.* xxi. p. 359; xxvii. p. 261.

[2] Marr, *Geol. Mag.* 1889, p. 414. Tornquist, *Geol. För. Stockholm Forhandl.* ix. (1887).

[3] Lossen, *Zeitsch. Deutsch. Geol. Ges.* xx. p. 216; xxii. p. 284; xxix. 612.

[4] Von Hauer, 'Geologie,' p. 216. Stache, *Jahrb. Geol. Reichsanstalt*, xxiii. p. 175; xxiv. 136, 334; *Verh. Geol. Reichs.* 1879, p. 216. Stache divided the greywacke zone of the eastern Alps into five pre-triassic groups: 1, Quartzphyllite group; 2, Kalkphyllite group; 3, Kalkthonphyllite group; 4, Group of the older greywackes (Silurian and Devonian); 5, Group of the Upper Coal and Permian rocks.

[5] *Verhandl. Geol. Reichsanst.* 1884, p. 25; *Zeitsch. Deutsch. Geol. Ges.* 1884, p. 277.

In the south-west of Russia (Podolia) and in Gallicia, an Upper Silurian area occurs in which there is almost perfect palæontological agreement with the Silurian rocks of the basin of the Baltic, but a great contrast to those of Bohemia, with which it has only a few brachiopods in common.[2]

North America.[3]—In the United States and Canada, Silurian rocks spread continuously over a vast territory, from the mouth of the St. Lawrence south-westwards into Alabama and westwards by the great lakes. They almost encircle and certainly underlie all the later Palæozoic deposits of the great interior basin. The rocks are most typically developed in the State of New York, where they have been arranged as in the subjoined table:—

Upper.	(4) Water-lime (*Tentaculites*, *Eurypterus*, and *Pterygotus*) Onondago salt group, consisting of red and grey marls, sandstones and gypsum, with large impregnation of common salt, but nearly barren of fossils.
	(3) Niagara shale and limestone (*Halysites*, *Favosites*, *Calymene Blumenbachii*, *Homalonotus delphinocephalus*, *Leptæna transversalis*, &c. ; also fish-remains (*Onchus*, *Glyptaspis*) in the shale in Pennsylvania. The Niagara Limestone may be paralleled with the Wenlock Limestone.
	(2) Clinton group (*Pentamerus oblongus*, *Atrypa reticularis*, *Monograptus clintonensis*, *Retiolites venosus*, &c.) This group may represent the Tarannon shales.
	(1) Medina group with Oneida conglomerate (*Modiolopsis orthonota*).
Lower.	(5) Cincinnati (Hudson River) group (*Syringopora*, *Halysites*, *Pterinea demissa*, *Leptæna sericea*, *Climacograptus bicornis*, *C. typicalis*, *Diplograptus pristis*, *D. putillus*). This group corresponds to the Caradoc rocks of Britain.
	(4) Utica group—Utica shale (*Leptograptus flaccidus*, *Diplograptus mucronatus*(?), *D. quadrimucronatus*, &c.) The shales of Norman's Kiln, near Albany, on the Hudson River, have yielded a large series of graptolites resembling the assemblage that characterises the Glenkiln shales of Scotland.
	(3) Trenton group. { Trenton limestone. Black River limestone. Birdseye limestone. } *Trinucleus concentricus*, *Orthis testudinaria*, *Murchisonia*, *Conularia*, *Orthoceras*, *Cyrtoceras*, &c.[4]
	(2) Chazy group—Chazy limestone (*Maclurea magna*, *M. Logani*, *Orthoceras*, *Illænus*, *Asaphus*).
	(1) Calciferous group (*Lingulella acuminata*, *Leptæna*, *Conocardium*, *Ophileta compacta*, *Orthoceras primigenium*, *Amphion*, *Bathyurus*, *Asaphus*, *Conocoryphe*, *Tetragraptus*, *Phyllograptus*, *Didymograptus*, *Clonograptus*, *Loganograptus*, *Diplograptus*, &c.) This group answers to the Welsh Arenig rocks.[5]

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[1] Meneghini, *Mem. R. Acad. Lincei*, 1880.

[2] F. Schmidt, 'Die Podolisch-galizische Silurformation,' St. Petersburg, 8vo, 1875.

[3] See especially the *Memoirs of the Geological Survey of Canada*, numerous monographs of Prof. James Hall, of Albany ; Walcott, *Monogr. U.S. Geol. Surv.* viii. (1884).

[4] Remains of ganoid fishes, like *Holoptychius* and *Asterolepis*, and of a chimæroid fish, have been found in what seems to be a representative of the Trenton group in Colorado. C. D. Walcott, *Bull. Geol. Soc. Amer.* iii. (1892) p. 153.

[5] According to researches by Mr. Selwyn, the so-called Quebec group as defined by Logan embraces three totally distinct groups of rock, belonging respectively to Archæan, Cambrian, and Lower Silurian horizons ; and in the fossiliferous belt of Logan's Quebec group are included—in a folded, crumpled and faulted condition—portions of subdivisions that lie elsewhere comparatively undisturbed, and embrace strata even lower than the Potsdam formation. *Trans. Roy. Soc. Canada*, vol. i. sect. iv. p. 1 (1882).

It is interesting to observe the number of genera and even of species common to the Silurian rocks of America and Europe, and the close parallelism in their order of appearance. Not a few of the widely diffused forms occur in Arctic America, so that a former migration along shallow northern waters between the two continents is rendered highly probable. Among these common species the following may be enumerated as occurring in the Upper Silurian rocks of New York, the coasts of Barrow Straits within the Arctic Circle, Britain, and the Baltic basin: *Stromatopora concentrica*, *Halysites catenularia*, *Favosites gotlandica*, *Orthis elegantula*, *Atrypa reticularis*. The genera of graptolites appear to have followed the same order of appearance and to have reached their full development and final decline at corresponding stages of the Silurian period on each side of the Atlantic. Among the crustacea, trilobites were the dominant order, represented in each region by a similar succession of genera, and even to some extent of species. And as these earlier forms of articulates waned, there appeared among them about the same epoch in the geological series, the eurypterids of the Water-lime of New York and of the Ludlow rocks of Shropshire and Lanarkshire.

Asia.—Silurian rocks have been recognised over a large part of the surface of the globe. They have been found, for example, running through the Cordilleras of South America on the one hand, and among the older rocks of the Himalaya chain on the other. The Salt Range of the Punjab contains thick masses of bright red marl, with beds of rock-salt, gypsum, and dolomite, over which lie purple sandstones and shales. These saliferous rocks have been already (p. 737) referred to as containing Cambrian fossils, but it is not yet known whether they include any representatives of the Silurian system.[1] In the regions of the Northern Punjab and Kashmir traces of Silurian organic remains have been discovered; while in the north of Kumaun such fossils have been found in considerable quantities.

From the province of Sze Chuen, in Western China, Richthofen has obtained numerous fossils which show the presence there of Middle and Upper Silurian rocks. Among the species, some are the same as those that occur in Western Europe, such as *Orthis calligramma*, *Leptæna sericea*, *Spirifer radiatus*, *Atrypa reticularis*, *Favosites fibrosa*, *Heliolites interstinctus*, *Halysites catenularia*, and others.[2]

Australasia.—In Australia the existence of the Silurian system has been proved by the discovery of a considerable number of characteristic fossils, among which are numerous graptolites of the genera *Climacograptus*, *Cœnograptus*, *Dichograptus*, *Dicranograptus*, *Didymograptus*, *Diplograptus*, *Monograptus*, *Loganograptus*, *Phyllograptus*, *Retiolites*, and *Tetragraptus*, with species of *Siphonotreta* and *Hymenocaris*, which occur in the Lower Silurian series of Victoria—an enormous series of sedimentary deposits, estimated by Mr. Selwyn to be not less than 35,000 feet thick—also many Upper Silurian fossils from New South Wales and Victoria, including such world-wide species as *Favosites gotlandica*, *Heliolites interstinctus*, *Calymene Blumenbachii*, *Encrinurus punctatus*, *Entomis tuberosa*, *Phacops caudatus*, *Atrypa reticularis*, *Strophomena pecten*, *Pentamerus Knightii*, *P. oblongus*, *Whitfieldia* (*Meristella*) *tumida*, *Orthoceras ibex*.[3] Near Bathurst and elsewhere, the Upper Silurian rocks of New South Wales have been much altered, sandstones passing into quartzites, slates into gneiss and hornblendic schists, and the coral-limestones into crystalline marbles with total obliteration of fossils.[4]

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[1] A. B. Wynne, *Mem. Geol. Surv. India*, xiv. See also *Palæont. Indica*. ser. 13, vol. i. (1887) p. 750; Medlicott and Blanford, 'Manual of the Geology of India,' 1879.

[2] Richthofen's 'China,' vol. iv. pp. 37, 50, where descriptions of the fossils are given by Kayser and Lindstrom.

[3] McCoy, 'Prodromus of Palæontology of Victoria;' L. G. de Koninck, 'Recherches sur les Fossiles Paléozoiques de la Nouvelle-Galles du Sud,' Brussels, 1876; R. Etheridge jun., 'Catalogue of Australian Fossils;' W. B. Clarke, 'Remarks on the Sedimentary Formations of New South Wales,' 4th edit.; C. S. Wilkinson, 'Notes on the Geology of New South Wales,' Sydney (1882).

[4] C. S. Wilkinson, *op. cit.*

In New Zealand some dark slates and crystalline limestones which form the mass of Mount Arthur, and from which a few graptolites, &c., have been obtained, are referred to the Lower Silurian series. They are much disturbed by hornblendic and syenitic eruptive rocks. To the Upper Silurian series are assigned some fossiliferous rocks from which *Calymene Blumenbachii*, *Spirifer radiatus*, *Stricklandinia lyrata*, &c., have been procured (Baton River series). A great part of the so-called metamorphic schists are probably Upper Silurian rocks.[1]

Section iii. Devonian and Old Red Sandstone.

In Wales and the adjoining counties of England, where the typical development of the Silurian system was worked out by Murchison, the abundant Silurian marine fauna disappears in the red rocks that overlie the Ludlow group. From that horizon upwards in the geological series, we have to pass through some 10,000 feet or more of barren red sandstones and marls, until we again encounter a copious marine fauna in the Carboniferous Limestone. It is evident that between the disappearance of the Silurian and the arrival of the Carboniferous fauna, very great geographical changes occurred over the site of Wales and the west of England. For a prolonged period, the sea must have been excluded, or at least must have been rendered unfit for the existence and development of marine life, over the area in question. The striking contrast in general facies between the organisms in the Silurian and those in the Carboniferous system, proves how long the interval between them must have been.

The geological records of this interval are still only partially unravelled and interpreted. At present the general belief among geologists is that, while in the west and north of Europe the Silurian sea-bed was upraised into land in such a way as to enclose large inland basins, in the centre and south-west the geographical changes did not suffice to exclude the sea, which continued to cover that region more or less completely. In the isolated basins of the west and north, a peculiar type of deposits, termed the Old Red Sandstone, is believed to have accumulated, while in the shallow seas to the south and east, a series of marine sediments and limestones was formed, to which the name of Devonian has been given. It is thus supposed that the Old Red Sandstone and Devonian rocks represent different geographical areas, with different phases of sedimentation and of life, during the long lapse of time between the Silurian and Carboniferous periods. A somewhat similar contrast between the lithological and palæontological characters of the corresponding formations in different parts of the United States and Canada, shows that in America also this geological period was marked by geological changes which produced distinct geographical conditions in adjacent regions.

That the Old Red Sandstone of Britain does represent the prolonged interval between Silurian and Carboniferous time can be demonstrated by innumerable sections, where the lowest strata of the system are found graduating downward into the top of the Ludlow group, and where its highest beds are seen to pass up into the base of the Carboniferous system. But the evidence is not everywhere so clear in regard to the true position of the Devonian rocks. That these rocks lie between Silurian and Carboniferous formations was long ago shown by Lonsdale from their fossils. But it is a curious fact that where the Lower Devonian beds are best developed, the Upper Silurian formations are scarcely to be recognised, or, if they occur, can hardly be separated from the so-called Devonian rocks. It is quite possible, therefore, that the lower portions of what has been termed the Devonian series may, in certain regions, to some extent represent what are elsewhere recognised as undoubted Ludlow or even perhaps Wenlock rocks.[1] We cannot suppose that the rich Silurian fauna died out abruptly at the close of the Ludlow epoch. We should be prepared for the discovery of Silurian rocks younger than the latest of those in Britain, such as Barrande showed to exist in his Étage H, or for a Devonian facies of fossils in rocks which are nevertheless regarded as Silurian. The rocks termed Lower Devonian may partly represent some of the later phases of Silurian life. On the other hand, the upper parts of the Devonian system might in several respects be claimed as fairly belonging to the Carboniferous system above.

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[1] Hector, 'Handbook of New Zealand,' p. 37.

J. B. Jukes proposed a solution of the Devonian problem, the effect of which would be to turn the whole of the Devonian rocks into Lower Carboniferous, and to place them above the Old Red Sandstone, which would thus become the sole representative in Europe of the interval between Silurian and Carboniferous time.[2] In the following descriptions an account will first be given of the Devonian type and then of the Old Red Sandstone.

I. DEVONIAN TYPE.

§ 1. General Characters.

ROCKS.—Throughout central and western Europe, the Devonian system presents a remarkable persistence of petrographical characters, indicating probably the prevalence of the same kind of physical conditions over the area during the period when the rocks were accumulated. The lower division consists mainly of sandstones, grits, and greywackes, with slates and phyllites. These rocks attain a great development on the Rhine, where they form the material through which the picturesque gorges of the river have been eroded. In the central zone, limestones predominate, often crowded with the corals and mollusks of the clearer water in which they were laid down, and in some cases actually representing former coral-reefs.[1] The upper series is more variable: being in some tracts composed of sandstones and shales, in others of shales and limestones, but everywhere presenting a more shaly thin-bedded aspect than the subdivisions beneath it. Considerable masses of diabase, tuff (schalstein), and other associated volcanic material are intercalated in the Devonian system in Devonshire and in Germany. As a rule, the rocks have been subjected to more or less disturbance, and have in some places been plicated and cleaved, and even metamorphosed into schists, quartzites, &c. In some districts, they have been invaded by large masses of granite and other eruptive rocks.

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[1] According to Kayser and Beyrich the limestones of the Hercynian series in the Harz and Nassau, together with Barrande's Upper Silurian Stages F, G, H, in Bohemia, are to be regarded as truly Devonian, and as being the deeper-water equivalents of the arenaceous series of the normal Lower Devonian series on the Rhine. (*Abhandl. Geol. Specialkarte Preussen*, II. Heft 4, 1878. *Zeitsch. Deutsch. Geol. Ges.* xxxiii. (1881), p. 628.)

[2] See his papers in *Journ. Roy. Geol. Soc. Ireland* (1865), i. pt. 1, new ser., and *Quart. Journ. Geol. Soc.* xxii. (1866), and his pamphlet on 'Additional Notes on Rocks of North Devon,' &c. (1867). The "Devonian question," as it has been called, has evoked a large number of papers, of which, besides those cited in subsequent pages, the following may be enumerated: Prof. Hull, *Q. J. Geol. Soc.* xxxv. (1879) p. 699; xxxvi. (1880) p. 255. A. Champernowne, *Geol. Mag.* v. 2nd Ser. (1878) p. 193; vi. (1879) p. 125; viii. (1881) p. 410. The general verdict has been adverse to the explanation of the structure of North Devon proposed by Jukes.

Among the economic products, the most important in Europe are the ores of iron, lead, tin, copper, &c., which occur in veins or lenticular masses through the Devonian rocks (Devon and Cornwall, Harz, &c.) In North America the Devonian rocks of Pennsylvania contain bands of "sand-rock" charged with petroleum.

LIFE.—An abundant cryptogamic flora covered the land during the ages that succeeded the Silurian period. As the remains of this vegetation are chiefly preserved in the Old Red Sandstone facies of deposits, it is described at p. 793. But the true Devonian rocks contain remains of marine vegetation, of which *Haliserites* is a frequent sea-weed in the Lower Devonian rocks of the Rhine. The fauna of the Devonian rocks is unequivocally marine. Among the more lowly forms of life are some of which the true zoological grade has been the subject of much uncertainty. Of these, the fossil known as *Calceola sandalina* (Fig. 349) has been successively described as a lamellibranch, a hippurite, and a brachiopod; but is now regarded as a rugose coral possessing an opercular lid. The *Pleurodictyum problematicum*, a well-known form of the Lower Devonian beds, is now classed with the *Favositidæ* among the perforate corals. The puzzling genus *Stromatopora* occurs in some of the limestones as abundantly and much in the same way as reef-building corals do in a modern coral-reef. The curious *Receptaculites*, already (p. 741) referred to, is a well-known Devonian fossil. The last graptolites are met with in the Devonian system. They are of the simple type so characteristic of the Upper Silurian rocks, and have chiefly been found in the Hercynian formation of the Harz.[2] The corals of the Devonian seas were both abundant in individuals and varied in their specific and generic range. Not a single species is common either to the Silurian system below or the Carboniferous above. Among the rugose forms, the genera *Cyathophyllum*, *Acervularia*, and *Cystiphyllum* are characteristic. The tabulate kinds belong chiefly to the important genera of *Favosites*, *Alveolites*, and *Heliolites*. *Calceola* and *Pleurodictyum*, already referred to, are important Lower Devonian corals, while *Phillipsastræa* is of great consequence among the coral-reefs of the Upper Devonian rocks. Of the echinoderms by far the most abundant representatives are crinoids, which occur in great profusion in the limestones, sometimes forming entire beds of rock. They belong chiefly to two families—the *Cyathocrinidæ*, simple pedunculate forms with five branching arms, and *Cupressocrinidæ* (wholly Devonian)

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[1] Dupont, *Bull. Acad. Roy. Belgique* (3) ii.; *Comptes rend.* Feb. 18, 1884. The frequent singularly lenticular character of Palæozoic limestones is explicable on the assumption that in many cases they grew up in patches after the manner of modern coral-reefs. The interrupted bands of shale in the Belgian Devonian limestones are regarded by M. Dupont as representing the lagoons that were filled up with muddy sediment.

[2] E. Kayser, *Abhandl. Specialkarte Preussen*, II. Heft 4, 1878.

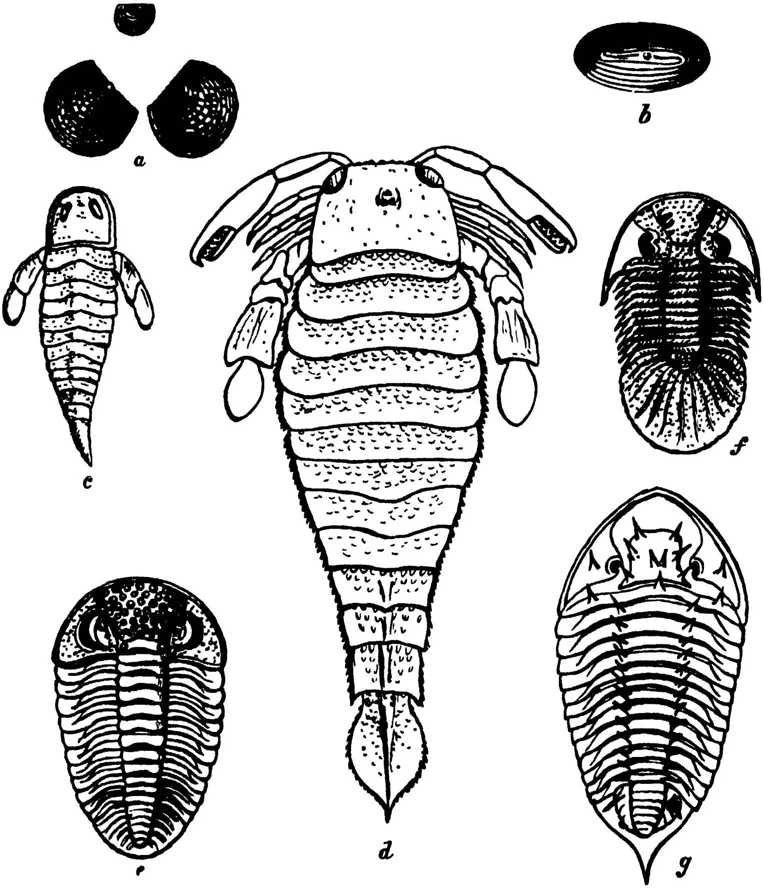

Fig. 348.—Devonian and Old Red Sandstone Crustacea.

a, Estheria membranacea, Pacht., nat. size and magnified (Lower Old Red Sandstone); *b*, Entomis (Cypridina) serrato-striata, Sandb., magnified (Upper Devonian); *c*, Eurypterus pygmæus, Salt. (Lower Old Red Sandstone); *d*, Pterygotus anglicus, Ag. (Lower Old Red Sandstone); *e*, Phacops latifrons, Bronn. (Lower Devonian); *f*, Bronteus flabellifer, Goldf. (Lower Devonian); *g*, Homalonotus armatus, Burm. (Lower Devonian).

having five arms which when folded up form a pentagonal pyramid, the accurate fitting of which recalls the ambulacra of sea-urchins. The Cystideans appear to have died out in the Devonian period. True starfishes also occur (*Helianthaster*, *Astropecten*, *Cœlaster*).

The known crustacean fauna of the Devonian period indicates a striking diminution in number both of individuals and of species of trilobites (Fig. 348). Most of the genera so abundant and characteristic among the Silurian rocks are now absent, the most frequent Devonian forms being species of *Phacops*, *Cryphæus*, *Dalmanites*, *Homalonotus*, and *Bronteus*. But some other Silurian genera still survived, especially *Acidaspis*, *Calymene*, *Cheirurus*, *Harpes*, *Lichas*, and *Proetus*. The ostracods are chiefly represented by the genus *Entomis* (*Cypridina*), which occurs in enormous numbers in some Upper Devonian shales ("Cypridinen-schiefer"). The phyllopods, eurypterids, and myriapods appear chiefly in the Old Red Sandstone, and are noticed on p. 794 (Fig. 348, *a*, *c*, *d*).

Among the mollusca of the Devonian rocks remains of the pteropod *Tentaculites* are not uncommon. The brachiopods (Fig. 349) now reached perhaps their maximum development, whether as regards individual abundance or number of specific and generic forms; more than 60 genera and 1100 species having been described. They compose three-fourths of the known Devonian fauna. While all the families of the class are represented, the most abundant are the *Spiriferidæ*, including the genera *Spirifer* (especially broad-winged species), *Cyrtia*, *Athyris* (*Spirigera*), *Uncites*, and *Atrypa* (*A. reticularis* ranging from the Upper Silurian through the Devonian system), and the *Rhynchonellidæ* (*Rhynchonella*, *Camarophoria*, *Pentamerus*). The Strophomenids or Orthids, so abundant in the Silurian rocks, are now represented by a waning number of forms, including the genera *Orthis*, *Strophomena*, *Streptorhynchus*, and *Leptæna*. The Productids made their appearance in Silurian times, but were more abundant in the Devonian seas, where their most frequent genera were *Chonetes* and *Productus*, both of which attained their maximum development in the Carboniferous period. One of the most characteristic and largest Devonian brachiopods is *Stringocephalus*—a genus allied to *Terebratula*, but entirely confined to this geological system (Fig. 349, *a*). Another characteristic terebratula-like form is *Rensseleria*.

The known Devonian lamellibranchs belong chiefly to the genera *Pterinea*, *Cardiola*, *Megalodon*, *Grammysia*, *Cucullæa*, *Curtonotus*, *Lucina*, and *Aviculopecten*; *Pterinea* being specially abundant in the lower, *Cucullæa* and *Curtonotus* in the upper subdivision of the system. The most important genera of gasteropods are *Euomphalus*, *Murchisonia*, *Loxonema*, *Macrocheilus*, *Acroculia* (*Capulus*) and *Pleurotomaria*, with the heteropods *Bellerophon* and *Porcellia*. The cephalopods embrace representatives of both the tetrabranchiate families of Nautilids and Ammonitids. Among the Nautilids are the genera *Clymenia*, an especially abundant form in some of the Upper Devonian shales and limestones, *Gyroceras*, *Orthoceras*, *Cyrtoceras*, *Hercoceras*, and *Gomphoceras*. The great family of the Ammonites had, in the Devonian waters, representatives of the more abundant coiled forms, in the characteristic genus *Goniatites*, and of the straight forms, in

Bactrites. Other Devonian genera are *Anarcestes*, *Aphyllites*, *Beloceras*, *Gephyroceras*, *Mimoceras*, *Pinacites*, *Prolecanites*, *Sporadoceras*, and *Tornoceras*. In the Devonian rocks of Central Europe, scanty remains of the great fish fauna of the Old Red Sandstone have been found, more especially in the Eifel, but seldom in such a state of preservation as to warrant their being assigned to any definite place in the zoological scale. Professor Beyrich has described from Gerolstein in the Eifel an undoubted species of *Pterichthys*, which, as it cannot be certainly identified with any known form, he has named *P. rhenanus*. A *Coccosteus* has been described by F. A. Roemer from the Harz, and more recently one has been cited from Bicken near Herborn by Von Koenen; but, as Beyrich points out, there may be some doubt as to whether the latter is not a *Pterichthys*.[1] A *Ctenacanthus*, seemingly undistinguishable from the *C. bohemicus* of

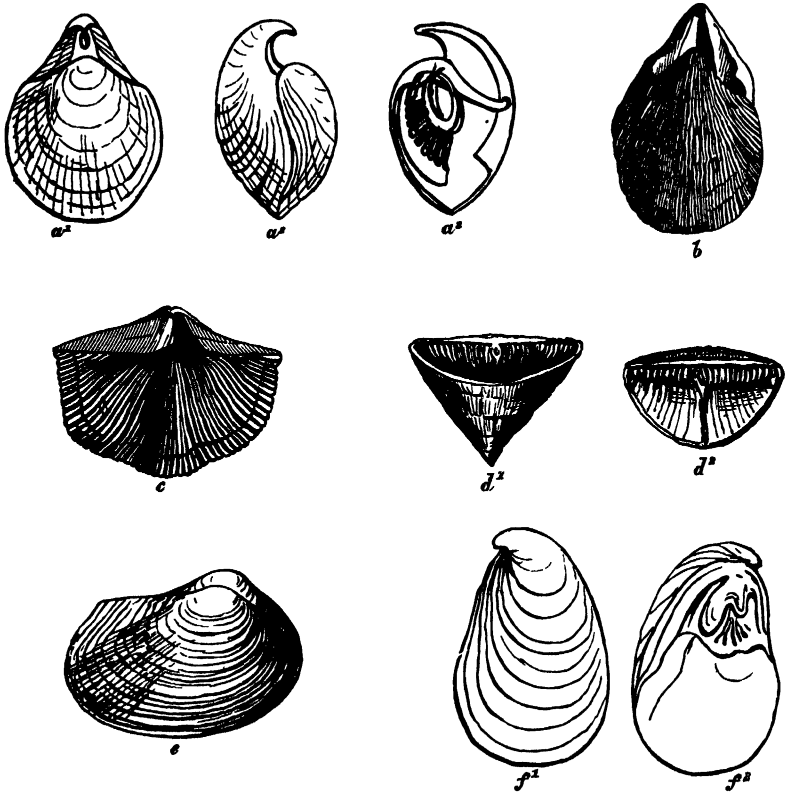

Fig. 349.—Devonian Fossils.

a^1, Stringocephalus Burtini, Def.; a^2, Do. lateral, and a^3, Do. internal view; b, Uncites gryphus, Def.; c, Spirifer Verneuili (disjunctus), Sow.; d^1, Calceola sandalina, Linn.; d^2, Opercular lid of do.; e, Cucullæa Hardingii, Sow.; f^1, f^2, Megalodon cucullatus, Sow.

[1] *Deutsch. Geol. Gesell.* xxix. 751.

Barrande's Étage G, has also been obtained from the Lower Devonian "Nereitenschichten" of Thuringia.[1] Two sharks (*Palædaphus devoniensis* and *Byssacanthus Gosseleti*) have been obtained from the Belgian and north of France area. The characteristic *Holoptychius nobilissimus* has been detected in the Psammite de Condroz, which in Belgium forms a characteristic sandy portion of the Upper Devonian rocks. These are interesting facts, as helping to link the Devonian and Old Red Sandstone types together. But they are as yet too few and unsupported to warrant any large deduction as to stratigraphical correlations between these types. The fishes of the Old Red Sandstone are noticed on p. 796.

§ 2. Local Development.

Britain.[2]—The name "Devonian" was first applied by Sedgwick and Murchison to the rocks of North and South Devon and Cornwall, whence a suite of fossils was obtained which Lonsdale pronounced to be intermediate in character between Silurian and Carboniferous. The passage of these strata into Silurian rocks has not been satisfactorily determined,[3] but they clearly graduate upward into Carboniferous strata. Considerable difference exists between the development of the Devonian rocks in the north and south of Devonshire. In the former area they consist of sandy and muddy materials in the form of sandstones, grits, and slates. In South Devonshire on the other hand they include thick masses of limestone and abundant volcanic intercalations in the form of tuffs (schalstein) and lavas (diabase, &c.) With these lithological contrasts there is a corresponding difference in the abundance and variety of organic remains, the calcareous rocks of Plymouth and Torquay being the chief repositories of fossils. Yet even at the best the Devonian rocks of this classical region, though they served as the type formations of the same geological age elsewhere, are much less clearly and fully developed than those of the Rhine country and other parts of the continent. It is rather from the sections and fossil collections of central Europe than from those of England that the stratigraphy and palæontology of the Devonian system are to be determined.

This system has long been grouped into three divisions, each more or less distinctly marked off by its palæontological characters. In Devonshire and West Somerset these divisions are arranged as follows:—

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[1] *Op. cit.* 423.

[2] Sedgwick and Murchison, *Trans. Geol. Soc.* 2nd ser. v. p. 633. Sedgwick, *Q. J. Geol. Soc.* viii. p. 1. Lonsdale, *Proc. Geol. Soc.* iii. p. 281. R. A. Godwin-Austen, *Trans. Geol. Soc.* (2) vi. p. 433. J. W. Salter, *Q. J. Geol. Soc.* xix. p. 474. T. M. Hall, *op. cit.* xxiii. p. 371. Etheridge, *Q. J. Geol. Soc.* xxiii. (1867) 568, where a copious bibliography up to date will be found; also *op. cit.* xxxvii. Address, p. 178. A. Champernowne and W. A. E. Ussher, *Q. J. Geol. Soc.* 1879, p. 532. A. Champernowne, *op. cit.* 1889, p. 369. W. A. E. Ussher, *Geol. Mag.* 1881, p. 441, *Quart. Journ. Geol. Soc.* 1890, p. 487. E. Kayser, *Neues Jahrb.* 1889, i. p. 189. The Devonian rocks of Cornwall and Devon have undergone much crumpling and have suffered considerable metamorphism. Their fossils are often singularly distorted, and mica has been almost everywhere abundantly developed in their argillaceous and calcareous portions. Much of the so-called "slate" or "killas" of these districts is a lustrous phyllite. On distortion of the fossils, see D. Sharpe, *Q. J. Geol. Soc.* iii.

[3] The recent discovery by Mr. Fox and Mr. Teall of radiolarian cherts at the Lizard in Cornwall, and the tracing of these cherts eastward into the Silurian tract of Gorran may furnish a base-line for determining the relations of Silurian and Devonian rocks in the south-west of England.

	Northern Type.	Southern Type.
Upper.	Pilton group. Slates and grits with calcareous seams (*Spirifer Verneuili*, *Athyris concentrica*, *Productus prælongus*, &c. Baggy group. Sandstones with *Cucullæa*, slates with *Lingula*, *Discina*. Pickwell-Down group. Red, green, grey, and purple slates and grits, generally unfossiliferous. Morte slates, unfossiliferous, passing down into the slates below.	Slates near Ashburton with *Spirifer Verneuili*, &c. Slates of Livaton with *Clymenia*. Red and green slates with *Posidonia venusta* and abundant *Entomis* (*Cypridina*) *serratostriata* (=Cypridinen-schiefer). Red and grey slates with volcanic tuffs. Chudleigh limestone with *Goniatites intumescens*, *G. lobatus*, *G. acutus*, *G. simplex*, *Cardiola retrostriata*, *Rhynchonella cuboides*, *R. acuminata*, *Atrypa reticularis*, *Spirifer bifidus*, *Productus subaculeatus*, &c.
Middle.	Ilfracombe slates; grey silvery slates with lenticular impure fossiliferous limestone, resting on grits and slates of Combe Martin (*Cyathophyllum cespitosum*, &c.)	Torquay and Plymouth limestones passing laterally into slates and volcanic rocks (*Stringocephalus Burtini*, *Uncites gryphus*, *Favosites polymorpha*, &c.) Slates and limestones of Hope's Nose (*Atrypa reticularis*, *Kayseria lens*, *Spirifer speciosus*, *S. curvatus*, *Rhynchonella procuboides*, &c. = Calceola beds).
Lower.	Hangman grits and slates (*Natica*, *Myalina*). Lynton group, grits and calcareous slates (*Spirifer hystericus*, *Chonetes sarcinalatus*, &c.) Foreland grits and slates.	Slates and greywackes (Cockington, Warberry, Meadfoot) with *Pleurodictyum problematicum*, *Homalonotus*, *Spirifer cultrijugatus*, *S. hystericus*, *Pterinea costata*, &c.

Lower.—The clay-slate of Looe, Cornwall, has yielded a species of *Pteraspis*, also *Pleurodictyum problematicum*. The lower gritty slates and limestone bands of North Devon contain, among other fossils, *Favosites* (*Pachypora*) *cervicornis*, *Cyathophyllum helianthoides*, *Petraia celtica*, *Pleurodictyum problematicum*, *Cyathocrinus* (two species), *Homalonotus* (two species), *Phacops laciniatus*, *Fenestella antiqua*, *Atrypa reticularis*, *Orthis arcuata*, *Spirifer canaliferus*, *S. lævicostus*, *Pterinea spinosa*, &c. The recent researches of Mr. Ussher and Professor Kayser have brought the Lower Devonian rocks of South Devon into closer palæontological relations with their equivalents on the continent. Among the species noted by these observers are—*Pleurodictyum problematicum*, *Spirifer hystericus*, *S. paradoxus*, *S. macropterus*, *S. cultrijugatus*, *Strophomena rhomboidalis*, *Rhynchonella daleidensis*, *Chonetes sarcinulata*, *C. semiradiata*, *Pterinea costata*, *Homalonotus gigas*,—an assemblage which resembles that in the Coblenzian stage of Rhineland.

Middle.—It is in this division that limestones are best developed and fossils are most abundant. Some of the limestones of South Devon are made up of corals, and from their lenticular or sporadic occurrence suggest that they were accumulated as reefs. Large masses of limestone rapidly die out laterally and are replaced by slates. In the Ashprington district a thick group of volcanic rocks consisting of breccias and tuffs (schalstein) and diabasic lavas appears entirely to take the place of the limestones. These volcanic ejections are traceable for many miles, sometimes dwindling down and giving place to limestones or slates, and again swelling out into considerable masses.[1] They appear to have been discharged from numerous small vents across the area of south Devonshire, but no trace of any similar material has yet been detected in the northern part of the county.

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[1] Champernowne on the Ashprington Volcanic Series, *Quart. Journ. Geol. Soc.* 1889, p. 369.

The palæontological evidence makes it abundantly clear that the limestones of Torquay and Plymouth represent the great Middle Devonian limestones of France, Belgium, and Germany—the Calcaire de Givet, and the Stringocephalen-Kalk and Calceola-Kalk of the Eifel. Near Torquay shaly limestones occur containing fossils that place them on the horizon of the Eifelian group or the Calceola beds of the continent, that is, the lower division of the Middle Devonian rocks. Among these fossils are *Atrypa reticularis*, *A. aspera*, *A. desquamata*, *Kayseria lens*, *Leptæna interstrialis*, *Pentamerus galeatus*, *Rhynchonella procuboides*, *Spirifer curvatus*, *S. speciosus*, *Streptorhynchus umbraculum*, *Productus subaculeatus*, *Phacops latifrons*, *Cyathophyllum heterophyllum*, *C. damnoniense*, *C. helianthoides*, *Cystiphyllum vesiculosum*, *Calceola sandalina*, *Favosites Goldfussi*, *Heliolites porosa*, *Stromatopora concentrica*. The massive limestones yield the characteristic fauna of the Givet or Stringocephalus limestone including the corals *Cyathophyllum helianthoides*, *C. damnoniense*, *Cystiphyllum vesiculosum*, *Alveolites*, *Favosites polymorpha*, *Striatopora denticulata*, *Amphipora ramosa*, *Heliolites porosa*, *Favosites Goldfussi*, *Stromatopora*, *Receptaculites Neptuni*, *Stringocephalus Burtini*, *Uncites gryphus*, *Terebratula Whidbornei*, *T. juvenis*, *Cyrtina heteroclita*, *Spirifer undiferus*, *Rhynchonella parallelopipeda*, *R. procuboides*, *R. pugnus*, *R. hammatoniensis*, *Pentamerus brevirostris*, *Leptæna interstrialis*, *Productus subaculeatus*, *Cypricardinia*, *Proetus*, *Bronteus*, &c.[1]

Upper.—In South Devon Upper Devonian rocks are now known to be well developed and to present palæontological representatives of the several zones which have been established in this division on the continent. Three such zones have been recognised. 1st, Massive limestones which pass down continuously into those of Middle Devonian age. They contain *Rhynchonella cuboides*, *R. acuminata*, *Atrypa reticularis*, *Athyris concentrica*, *Spirifer bifidus*, *S. lineatus*, *Productus subaculeatus*, *Waldheimia Whidbornei*, *Merista plebeia*, *Conocardium*, *Harpes*, *Stromatopora Hüpschii*, *Actinostroma clathratum* (?) &c. 2nd, Goniatite beds which, overlying and passing down into the limestones, are marked by the presence of numerous goniatites (*G. intumescens*, *G. complanatus*, *G. multilobatus*, *G. acutus*, *G. simplex*), with *Cardiola retrostriata*, *Myalina* sp., *Sanguinolaria*, *Bactrites*, *Alveolites*. 3rd, Cypridina-slates, containing ostracods (*Entomis* or *Cypridina serratostriata*) and Clymenias (*C. lævigata* and other species). These three zones may be paralleled respectively with the Frasnien and Fammenien group of the Franco-Belgian area and with the Goniatite (Adorf, Iberg) limestone, Cypridina slates and Clymenia limestone of the Eifel and Rhine.

In North Devon this palæontological grouping has not been so satisfactorily made out; but in that region there is an insensible gradation upwards through various sandy and muddy sediments into the Culm or Carboniferous system. The micaceous flaggy sandstones of Baggy Point contain *Cucullæa trapezium*, *C. Hardingii*, *Avicula damnoniensis*, *Lingula squamiformis*, *Discina*, *Rhynchonella laticosta*, *Strophalosia productoides*, *Spirifer disjunctus*, &c. The greenish slates and calcareous bands of Pilton near Barnstaple have yielded some characteristic fossils of the uppermost part of the Devonian system, such as *Petraia celtica*, *Cyathocrinus pinnatus*, *Spirifer Verneuili*, *Athyris concentrica*, *Streptorhynchus crenistria*, *Productus prælongus*, *Strophalosia productoides*, *S. caperata*, *Rhynchonella pleurodon*, and *Chonetes hardrensis*. Remains of land-plants are found in the Upper Devonian rocks of North Devon (*Sagenaria* (*Knorria*) *veltheimiana*, *Archæopteris* (*Palæopteris*) *hibernica*). The higher red and yellow sandy portions of these rocks shade up insensibly at Barnstaple in North Devon into strata which by their fossils are placed at the base of the Carboniferous Limestone series. But in no other British locality save in Devonshire can such a passage be observed. In all other places, the Carboniferous system, where its true base can be seen, passes down into the red sandy and marly strata of the Upper Old Red Sandstone without marine fossils.

Central Europe.—A large tract of Devonian rocks extends across the heart of Europe from the north of France through the Ardennes, the south of Belgium, Rhenish Prussia, Westphalia and Nassau. But that the same rocks have a much wider spread under younger formations which cover them is shown by their reappearance far to the west in Brittany,[1] and to the east in the Harz and the Thuringer Wald. They present a much clearer sequence of strata than their British equivalents, for they can be seen in many places to pass down into Silurian strata as well as to graduate upward into the Carboniferous system. In the Belgian and Eifelian tracts they have been subdivided as under:—

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[1] Ussher, *Quart. Journ. Geol. Soc.* 1890, p. 501. E. Kayser, *Neues Jahrb.* 1889, i. p.185.

	Belgium and the North of France.[2]	Rhineland.[3]
UPPER.	**Famennien**, consisting of two facies, one sandy, the other shaly. (*b*) Psammites du Condros (Condrusien), in which six zones are distinguished (*Cucullæa Hardingii*, *Spirifer Verneuili*, *Rhynchonella Dumonti*, *Orthis crenistria*, *Phacops latifrons*, *Archæopteris hibernica*, *Sphenopteris flaccida*, &c. (*a*) Schistes de Famenne, divisible into four zones (1) that of *Spirifer distans*, (2) of *Rhynchonella letiensis*, (3) of *Rhynchonella Dumonti*, (4) of *Rhynchonella Omaliusi*.	Younger group of Cypridina shales, with *Entomis* (*Cypridina*) *serratostriata*, *Avicula* (*Posidonia*) *venusta*, *Phacops cryptophthalmus*, and limestones (Kramenzelkalk) with numerous Clymenias (*C. lævigata*, *C. undulata*, *C. striata*, &c.), and Goniatites.
	Frasnien, varying in composition and organic contents in different parts of the Devonian basins. In the Dinant basin it consists of (*b*) Schistes de Matagne (*Goniatites retrorsus*, *Cardium palmatum*, *Camarophoria tumida*, *Bactrites subconicus*, *Entomis* [*Cypridina*] *serrato-striata*). (*a*) Calcaires et schistes de Frasne, shales and lenticular limestones, sometimes of great thickness, with abundant fossils (*Bronteus flabellifer*, *Goniatites intumescens*, *Spirifer Verneuili*, *Sp. pachyrhynchus*, *Sp. orbelianus*, *Spirigera concentrica*, *Atrypa reticularis*, *Rhynchonella cuboides*, *Pentamerus brevirostris*, *Camarophoria formosa*, *Receptaculites Neptuni*).	Brachiopod limestone directly overlying the Middle Devonian limestone, and containing *Rhynchonella cuboides*, *R. pugnus*, *R. acuminata*, *Spirifer Verneuili*, *Camarophoria formosa*, *Productus subaculeatus*, *Goniatites intumescens*. Iberg limestone of Harz, Adorf limestone of Waldeck, shales of Budesheim in the Eifel, with *Goniatites intumescens*, *Rhynchonella cuboides*, and *Cardiola retrostriata*. The prevalence of this Rhynchonella has led to the group being called the "Cuboides beds," and the Goniatite has given the name of, "Intumescens beds."
MIDDLE.	**Givetien**.—The great limestone of the middle Devonian series, well seen at Givet, above Dinant on the Meuse, 400 metres thick. Among the abundant characteristic fossils are *Spirifer mediotextus*, *Sp. undiferus*, *Stringocephalus Burtini*, *Uncites gryphus*, *Megalodon cucullatus*, *Murchisonia coronata*, *M. bilineata*, *Cyathophyllum quadrigeminum*, *Heliolites porosa*. In the basin of Namur the conglomerate of Pairy-Bony lies below the limestone, and contains a band of sandstone with plants (*Lepidodendron gaspianum*). **Eifélien**, Shales (Schistes de Couvin), with *Calceola sandalina*, *Phacops latifrons*, *Bronteus flabellifer*, *Spirifer curvatus*, *Sp. subcuspidatus*, *Sp. elegans*, *Spirigera concentrica*, *Pentamerus galeatus*, *Strophalosia productoides*, &c.	(*b*) Stringocephalus group, consisting of the great Eifel limestone with underlying crinoidal beds (*Stringocephalus Burtini*, *Uncites gryphus*, *Spirifer undatus*, *Productus subaculeatus*, *Pentamerus galeatus*, *Atrypa reticularis*, *Macrocheilus arculatus*, *Pleurotomaria delphinuloides*, *Murchisonia bilineata*, *Megalodon cucullatum*, and many corals and crinoids). (*a*) Calceola group,—marly limestones with *Athyris concentrica*, *Camarophoria microrhyncha*, *Atrypa reticularis*, *Merista plebeia*, *Spirifer speciosus*, *S. curvatus*, *Pentamerus galeatus*, *Rhynchonella parallelopipeda*, *Orthis striatula*, *Calceola sandalina*, *Cyathophyllum heliantoides*, *Cystiphyllum vesiculosum*, *Heliolites porosa*, *Alveolites*, *Favosites*, *Stromatopora*, *Phacops Schlotheimi*, &c., resting upon impure shaly ferruginous limestone and greywacke, marked by an abundance of *Spirifer cultrijugatus*, *Rhynchonella orbignyana*, *Atrypa reticularis*, *Phacops latifrons*, &c.

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[1] A ridge of Devonian rocks stretches eastward under the south of England (where its existence has been proved by well-borings at London), and no doubt joins the Devonian area of the Boulonnais.

[2] See especially Gosselet's 'Esquisse Géologique,' and his great memoir on the Ardennes already cited.

[3] See the series of elaborate papers by E. Kayser in the *Zeitschrift Deutsch. Geol. Gesell.* vols. xxii. (1870) to xxxiii. (1881), and *Abhand. Geol. Specialkarte Preussen*, Band II. Heft 4, 1878; *Jahrb. Preuss. Geol. Landesanst.* 1881, and subsequent volumes. Prof. F. von Sandberger has published a valuable paper, 'Ueber die Entwickelung der unteren Abtheilung des Devonischen Systems in Nassau,' Wiesbaden, 1889, in which he compares the formations with those of other countries.

	Belgium and the North of France.	Rhineland.
LOWER.	**Coblenzien**, composed of greywacke, sandstones, shales, and conglomerate, having a united thickness of sometimes 7000 or 8000 feet, and divisible into five sub-groups as under:— 5. Greywacke of Hierges with (*b*) Zone of *Spirifer cultrijugatus*, *Calceola sandalina*. (*a*) Zone of *Spirifer arduennensis*, *Pterinea lineata*. 4. Red slates of Vireux and conglomerate of Burnot. 8. Black sandstone of Vireux (Ahrien). 2. Greywacke of Montigny with *Spirifer paradoxus*, *Athyris undata*, *Strophomena depressa* (Hundsruckien). 1. Sandstone of Anor (Taunusien). **Gedinnien**, comprising an upper group of shales and sandstones and a lower group of fossiliferous shales, quartzo-phyllades, quartzites, and conglomerates. The fossils in the lower group comprise *Dalmanites*, *Homalonotus Roemeri*, *Primitia Jonesii*, *Tentaculites grandis*, *T. irregularis*, *Spirifer Mercuri*, *Orthis Verneuili*, *Pterinea ovalis*, &c. The base of the Devonian system lies unconformably on Cambrian rocks.	Coblenz group (Spirifer sandstone) divisible into the three following sub-groups:— (*c*) Upper greywacke and slate (Coblenz, Ems, Daleiden) with *Ctenocrinus decadactylus*, *Spirifer auriculatus*, *S. curvatus*, *S. paradoxus*, *Atrypa reticularis*, *Chonetes dilatata*, *Homalonotus lævicauda*, *Cryphæus laciniatus*. (*b*) Coblenz quartzite probably on the horizon of the Burnot conglomerate in the Eifel. (*a*) Greywacke with *Stropomena laticosta*, *Orthis circularis*, *Spirifer dunensis*, *Homalonotus ornatus*, *H. crassicauda*. Slates (Hundsruck, Taunus) with numerous trilobites (*Homalonotus ornatus*, *Phacops Ferdinandi*, *Cryphæus*, *Dalmanites*, *Orthoceras*, *Goniatites*, &c.) Taunus quartzite, Siegen grauwacke (*Spirifer primævus*, *S. hystericus*, *Rensseleria*, &c.) Sandstones, slates, phyllites, arkoses, ending downwards in conglomerates.

In the Harz, according to the researches of F. Roemer[1] and K. A. Lossen,[2] the Devonian system, which is there largely developed, consists of (1) a lower group of quartzites, greywackes, flinty slates, clay-slates, and associated bands of diabase (Taunus quartzite, Hundsruck shales, &c., resting upon the graptolitic Wieda shales and Tanne greywacke; (2) a middle group composed of (*a*) Calceola-beds (*Spirifer cultrijugatus*, *Calceola sandalina*) and (*b*) Stringocephalus limestone (consisting of a lower crinoidal band and a massive limestone; and (3) an upper group consisting of (*a*) Cuboides-beds, limestones and marls, (*b*) Goniatite shales, (*c*) Cypridina shales. The eastern part of the region consists mainly of greywackes and slates which, with their associated igneous rocks attaining a great thickness in the Wieda slates, contain a number of simple graptolites and in the limestones underneath yield abundant trilobites belonging to genera familiar in the Upper Silurian rocks (*Dalmanites*, *Cryphæus*, *Phacops*, *Bronteus*, *Acidaspis*).

Representatives of the Devonian system reappear with local petrographical modifications, but with a remarkable persistence of general palæontological characters, in Eastern Thuringia, Franconia, Saxony, Silesia, the north of Moravia, and East Gallicia. Among the crumpled formations of the Styrian Alps, the evidence of organic remains has revealed the presence of Upper Devonian rocks with abundant Clymenias, Middle Devonian limestones with the characteristic *Stringocephalus* and numerous corals, and Lower limestones and slates with cephalopods and brachiopods.[3] Perhaps in other tracts of the Alps, as well as in the Carpathian range, similar shales, limestones, and dolomites, though as yet unfossiliferous, but containing ores of silver, lead, mercury, zinc, cobalt, and other metals, may be referable to the Devonian system.

To the west of central Europe the system has been recognised by its fossils in the Boulonnais, where its middle and upper members (Givetian, Frasnian, Famennian) are well exposed. In Normandy and Maine, sandstones (with *Orthis Monnieri*), are followed by limestones (with *Homalonotus*, *Cryphæus*, *Phacops*, &c.), and by upper greywackes and shales (with *Pleurodictyum problematicum*).[4] In Brittany also, Devonian strata are found, including representatives of the Famennian groups with

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[1] 'Versteinerungen des Harzgebirges,' 1843; 'Rheinisch. Uebergangsgebirge,' 1844.

[2] 'Geologisch. Uebersichtskarte Harz,' 1881.

[3] G. Stache, *Zeitsch. Deutsch. Geol. Ges.* 1884, p. 358; Frech, *op. cit.* 1887, p. 660 (and authors there cited); 1891, p. 672.

[4] Oehlert, *Bull. Soc. Géol. France*, xvii. (1889) p. 742.

Cypridinas and Goniatites, shales and limestones with Eifelian cephalopods, *Pleurodictyum problematicum* and *Spirifer cultrijugatus*, and a series of greywackes, sandstones, and shales with *Chonetes sarcinulata, Phacops latifrons*, &c.[1] In this region lies the limestone of Erbray (Loire Inférieure) so fully described by Barrois who, from its abundant corals, numerous brachiopods and gasteropods, and its trilobites of the genera *Calymene, Phacops, Dalmanites, Proëtus, Harpes, Bronteus and Cheirurus*, places it in the Gedinnian group at the base of the Lower Devonian series, and compares it with the Hercynian limestones of the Harz.[2] In the remarkable oasis of ancient rocks which has been already referred to as forming a conspicuous feature among the younger formations of Languedoc representatives of the three great divisions of the Devonian system have recently been worked out by F. Frech.[3] Again, the central Silurian zone of the Pyrenees is flanked on the north and south by bands of Devonian rocks (with broad-winged spirifers and other characteristic fossils), which have been greatly disturbed and altered. In the Asturias, according to Barrois, a mass of strata about 3280 feet thick contains representatives of the three divisions of the Devonian series, and has yielded an abundant fauna, numbering upwards of 180 species, among which the corals and brachiopods are specially abundant.[4]

Throughout central Europe there occurs, in many parts of the Devonian areas, evidence of contemporaneous volcanic action in the form of intercalated beds of diabase, diabase-tuff, schalstein, &c. These rocks are conspicuous in the "greenstone" tract of the Harz, in Nassau, Saxony, Westphalia, and the Fichtelgebirge. Here and there, the tuff-bands are crowded with organic remains. It is also deserving of remark that over considerable areas (Ardennes, Harz, Sudeten-Gebirge, &c.) the Devonian sedimentary formations have assumed a more or less schistose character, and appear as quartzophyllades, quartzites, and other more or less crystalline rocks which were at one time supposed to belong to the "Archæan" series, but in which recognisable Devonian fossils have been found (*ante*, p. 619). At numerous places, also, they have been invaded by masses of granite, quartz-porphyry, or other eruptive rocks, round which they present the characteristic phenomena of contact-metamorphism (pp. 605, 606). These changes may have led to the subsequent development of the abundant mineral veins (Devon, Cornwall, Westphalia, &c.), whence large quantities of iron, tin, copper, and other metals have been obtained.

Russia.—In the north-east of Europe the Devonian and Old Red Sandstone types appear to be united, the limestones and marine organisms of the one being interstratified with the fish-bearing sandstones and shales of the others. In Russia, as was shown in the great work 'Russia and the Ural Mountains,' by Murchison, De Verneuil and Keyserling, rocks intermediate between the Upper Silurian and Carboniferous Limestone formations cover an extent of surface larger than the British Islands.[5] This wide development arises, not from the thickness, but from the undisturbed horizontal character of the strata. Like the Russian Silurian deposits, they remain to this day nearly as flat and unaltered as they were originally laid down. Judged by mere vertical depth, they present but a meagre representation of the massive Devonian greywacke and limestone of Germany, or of the Old Red Sandstone of Britain. Yet, vast as is the area over which they constitute the surface-rock, it probably forms only a small portion of their total extent; for they rise up from under the newer formations along the flank of the Ural chain. It would thus seem that they spread continuously across the whole breadth of Russia in Europe. Though almost everywhere undisturbed, they afford evidence of terrestrial oscillation immediately previous to their deposition, for they gradually overlap Upper and Lower Silurian rocks.

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[1] Barrois, *Ann. Soc. Géol. Nord*, iv. xvi.

[2] 'Faune du Calcaire d'Erbray,' *Mém. Soc. Géol. Nord*, iii. (1889).

[3] *Zeitsch. Deutsch. Geol. Ges.* xxxix. (1887) p. 402.

[4] "Recherches sur les Terrains anciens des Asturies," &c., *Mém. Soc. Géol. Nord*, ii.

[5] Besides the great work of these three pioneers the student will find much recent information regarding Russian geology in the *Mémoires du Comité Géologique* of Russia. See for Devonian data T. Tschernyschew, vols. i. iii. (a detailed memoir on the lower, middle, and upper divisions of the system in the Ural region).

The chief interest of the Russian rocks of this age, as was first signalised by Murchison and his associates, lies in the union of the elsewhere distinct Devonian and Old Red Sandstone types. In some districts, these rocks consist largely of limestones, in others of red sandstones and marls. In the former, they present mollusks and other marine organisms of known Devonian species ; in the latter, they afford remains of fishes, some of which are specifically identical with those of the Old Red Sandstone of Scotland. The distribution of these two palæontological facies in Russia is traced by Murchison to the lithological characters of the rocks, and consequent original diversities of physical conditions, rather than to differences of age. Indeed, cases occur where, in the same band of rock, Devonian shells and Old Red Sandstone fishes lie commingled. In the belt of the formation which extends southwards from Archangel and the White Sea, the strata consist of sands and marls, and contain only fish remains. Traced through the Baltic provinces, they are found to pass into red and green marls, clays, thin limestones, and sandstones, with beds of gypsum. In some of the calcareous bands such fossils occur as *Orthis striatula*, *Spiriferina prisca*, *Leptæna productoides*, *Spirifer Anossofi*, *S. Archiaci*, *S. Verneuili*, *Rhynchonella cuboides*, *Spirorbis omphaloides*, and *Orthoceras subfusiforme*. The lower parts of the series contain *Osteolepis*, *Dipterus*, *Diplopterus*, and *Asterolepis* (*Homosteus*), while in the higher beds *Holoptychius*, *Glyptosteus*, and other well-known fishes of the Upper Old Red Sandstone occur. Followed still farther to the south, as far as the watershed between Orel and Woronesch, the Devonian rocks lose their red colour and sandy character, and become thin-bedded yellow limestones, and dolomites with soft green and blue marls. Traces of salt deposits are indicated by occasional saline springs. It is evident that the geographical conditions of this Russian area during the Devonian period must have resembled those of the Rhine basin and central England during the Triassic period. There is an unquestionable passage of the uppermost Devonian rocks of Russia into the base of the Carboniferous system, but a complete break between them and the highest Silurian strata. The lowest parts of the British Old Red Sandstone, containing *Pterygotus*, *Cephalaspis*, *Pteraspis*, &c., are wanting. Devonian rocks have been recognised in other parts of the vast Russian empire, across Siberia in the Altai mountains, in Asia Minor, and in Africa.

North America.—The Devonian system, as developed in the Northern States, and eastern Canada and Novia Scotia, presents much geological interest in the union which it contains of the same two distinct petrographical and biological types found in Europe. Traced along the Alleghany chain, through Pennsylvania, into New York, the Devonian rocks are found to contain a characteristic suite of marine organisms comparable with those of the Devonian system of Europe. But on the eastern side of the great range of Silurian hills in the north-eastern States, we encounter in New Brunswick and Nova Scotia a succession of red and yellow sandstones, limestones, and shales nearly devoid of marine organisms, yet full of land-plants, and with occasional traces of fish remains. The marine type is well developed above the Silurian series in Nevada.

The marine or Devonian type has been grouped in the following subdivisions by the geologists of New York :—

UPPER DEVONIAN.	Catskill Red Sandstone, with fish remains (*Holoptychius*).
	Chemung group (*Spirifer Verneuili*).
	Portage group (*Goniatites*, *Cardiola*, *Clymenia*).
	Genesee group (*Rhynchonella* cf. *cuboides*).
MIDDLE DEVONIAN.	Hamilton group (*Phacops*, *Homalonotus*, *Cryphæus*).
	Marcellus group (*Goniatites*).

Corniferous limestone (*Spirifer acuminatus*, *S. gregarius*, *Dalmanites*, *Proëtus*).
Onondaga limestone, Schoharie grit, Cauda-galli grit. (This and the Corniferous limestone are bracketed together as the Upper Helderberg group.)

LOWER DEVONIAN.
Oriskany sandstone (*Spirifer arenosus*, *Rensseleria ovoides*).
Lower Helderberg group consisting of
- (*c*) Upper Pentamerus limestone (*Pentamerus pseudo-galeatus*).
- (*b*) Delthyris limestone (*Meristella lævis*).
- (*a*) Lower Pentamerus limestone (*Pentamerus galeatus*).

In the Lower Devonian series, traces of terrestrial plants (*Psilophyton*, *Caulopteris*, &c.) have been detected, even as far west as Ohio. Corals (cyathophylloid forms, with *Favosites*, *Syringopora*, &c.) abound especially in the Corniferous Limestone, perhaps the most remarkable mass of coral-rock in the American Palæozoic series, and from which Hall has made a magnificent collection of specimens. Among the brachiopods are species of *Pentamerus*, *Stricklandinia*, *Rhynchonella*, and others, with the characteristic European form *Spirifer cultrijugatus*, and the world wide *Atrypa reticularis*. The trilobites include the genera *Dalmanites*, *Proëtus*, and *Phacops*. Remains of fishes occur in the Corniferous group, consisting of ichthyodorulites and teeth of cestraciont and hybodont placoids, with plates, bones, and teeth of some peculiar ganoids (*Macropetalichthys*, *Onychodus*).

In the Marcellus shale, Hamilton beds, and Genesee shale remains of land-plants occur, but much less abundantly than among the rocks of New Brunswick. Brachiopods are especially abundant among the sandy beds in the centre of the formation. They comprise, as in Europe, many broad-winged spirifers (*S. mucronatus*, &c.), with species of *Productus*, *Chonetes*, *Athyris*, &c. The earliest American Goniatites have been noticed in these beds. Newberry has described a gigantic fish (*Dinichthys*) from the Black Shale of Ohio.

The Portage and Chemung groups have yielded land-plants and fucoids, also some crinoids, numerous broad-winged spirifers, with *Aviculæ* and a few other lamellibranchs. These strata, in the New York region, consist of shales and laminated sandstones, which there attain a maximum thickness of upwards of 2000 feet, but die out entirely towards the interior. They are covered by a mass of red sandstones and conglomerates—the Catskill group, which is 2000 or 3000 feet thick in the Catskill Mountains, and thickens along the Appalachian region to 5000 or 6000 feet. These red arenaceous rocks bear a striking similarity in their lithological and biological characters to the Old Red Sandstone of Europe. As a whole they are unfossiliferous, but they have yielded some ferns like those of the Upper Old Red Sandstone of Ireland and Scotland (*Archæopteris*), some characteristic genera of fish, as *Holoptychius* and *Bothriolepis*, and a large lamellibranch closely resembling the Irish *Anodonta*. The Old Red Sandstone development, found on the eastern side of the crystalline ridge which runs southwards from Canada far into the States, is described at p. 803.

Asia.—From south-western China, Richthofen brought a series of marine fossils which show the presence there of strata probably referable to Middle and Upper Devonian horizons. Out of 28 species named by Kayser, no fewer than 13 are cosmopolitan, including such familiar forms as *Rhynchonella cuboides*, *R. pugnus*, *Pentamerus galeatus*, *Atrypa reticularis* (var. *desquamata*), *Merista plebeia*, *Spirifer Verneuili*, *Orthis striatula*, *Productus subaculeatus*, *Strophalosia productoides*, *Aulopora tubæformis*.[1]

Australasia.—In New South Wales, the presence of Devonian rocks was determined by W. B. Clarke from the evidence of fossil remains. The thickness of strata (sandstones, quartzites, conglomerates, shales and limestones) is in some places estimated at not less than 10,000 feet, passing down into Silurian and upwards into Carboniferous strata. Among the numerous fossils are many forms familiar in corresponding strata in

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[1] Richthofen, 'China,' vol. iv. p. 75.

Europe and America, such as *Cyathophyllum damnoniense*, *Favosites reticulata*, *F. fibrosa*, *F. Goldfussi*, *Heliolites porosa*, *Chonetes laguessiana* (*hardrensis*), *Orthis striatula*, *Rhynchonella pleurodon*, *R. pugnus*, *Atrypa reticularis*, *Spirifer Verneuili*.[1] In Victoria certain limestones found at Bindi on the Tambo river and elsewhere have yielded characteristically Middle Devonian fossils, including *Favosites Goldfussi*, *Spirifer lævicostatus*, *Chonetes australis*, and a placoderm fish. With these rocks are associated contemporaneous felsitic lavas and tuffs. Other strata are referred to the Upper Devonian series.[2]

Devonian rocks play an important part in the structure of New Zealand. To the lower part of the system are assigned quartzites, cherts, and limestones, which in the South Island at Reefton have yielded *Spirifer vespertilio* and *Homalonotus expansus*. To the Upper Devonian series should probably be referred the enormously thick Te Anau group of "greenstone-breccias, aphanite-slates, diorite-sandstones, with great contemporaneous flows and dykes of diorite, serpentine, syenite, and felsite." These rocks form important mountain ranges in the South Island, and at Reefton are the matrix of the auriferous reefs. They rest unconformably on the Lower Devonian and pass up into the Maitai series (Carboniferous).[3]

II. OLD RED SANDSTONE TYPE.

§ 1. General Characters.

Under the name of Old Red Sandstone, is comprised a vast and still imperfectly described series of red sandstones, shales, and conglomerates, intermediate in age between the Ludlow rocks of the Upper Silurian and the base of the Carboniferous system in Britain. These rocks were termed "Old" to distinguish them from a somewhat similar series overlying the Coal-measures, to which the name "New" Red Sandstone was applied. When the term Devonian was adopted it speedily supplanted that of Old Red Sandstone, inasmuch as it was founded on a type of marine strata of wide geographical extent, whereas the latter term described what appeared to be merely a British and local development. For the reasons already given, however, it is desirable to retain the title Old Red Sandstone as descriptive of a remarkable suite of deposits to which there is little or nothing analogous in typical Devonian rocks. The Old Red Sandstone of Europe is almost entirely confined to the British Isles. It was deposited in separate areas or basins, the sites of some of which can still be traced. Their diversities of sediment and discrepance of organic contents point to the absence, or at least rare existence, of any direct communication between them. It was maintained many years ago by Fleming and still more explicitly by Godwin-Austen, and was afterwards enforced by A. C. Ramsay, that these basins were lakes or inland seas. The character of the strata, the absence of unequivocally marine fossils, the presence of land-plants and of numerous ganoid fishes, which have their modern representatives in rivers and lakes, suggest and support this opinion, which has been generally adopted by geologists.[4] The red arenaceous and marly strata which, with their fish-remains and land-plants, occupy a depth of many thousand feet between the top of the Silurian and the base of the Carboniferous systems, are regarded as the deposits of a series of lakes or inland seas formed by the uprise of portions of the Silurian sea-floor. The length of time during which these lacustrine basins must have existed is shown, not only by the thickness of the deposits formed in them, but by the complete change which took place in the marine fauna between the Silurian and Carboniferous periods. The prolific fauna of the Wenlock and Ludlow rocks was driven away from western Europe by the geographical revolutions which, among other changes, produced the lake-basins of the Old Red Sandstone. When a marine population—crinoids, corals, and shells—once more overspread that area, it was a completely different one. So thorough a change must have demanded a long interval of time.

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[1] See the authors cited on p. 776, note.

[2] R. A. F. Murray, 'Victoria—Geology and Physical Geology,' 1887.

[3] Hector, 'Handbook of New Zealand,' p. 36.

[4] For a history of opinion on this subject see *Trans. Royal Soc. Edin.* xxviii. 1869, p. 346.

ROCKS.—As shown by the name of the type, red sandstone is the predominant rock. The colour varies from a light brick-red to a deep chocolate-brown, and occasionally passes into green, yellow, or mottled tints. The sandstones are for the most part granular siliceous rocks, wherein the component grains of clear quartz are coated and held together by a crust of earthy ferric oxide. In no part of the geological record is the prevalence of this red material more marked than in the Old Red Sandstone. The conditions that led to the precipitation of this oxide in such quantity are not yet well understood.[1] Scattered pebbles of quartz or of various crystalline rocks are frequently noticeable among the sandstones, and this character affords a passage into conglomerate. The latter rock forms a conspicuous feature in many Old Red Sandstone districts. It varies in thickness from a mere thin bed up to successive massive beds, having a united thickness of several thousand feet. The pebbles vary much in composition and size. They consist of quartz, quartzite, greywacke, granite, syenite, quartz-porphyry, gneiss, felsite, or any durable material, and their varying nature serves to distinguish some bands of conglomerate from others. They are of all sizes up to blocks eight feet or more in length. They are sometimes tolerably angular, particularly where the conglomerate rests upon schists or other rocks which weather into angular blocks. In the upper Old Red Sandstone, thick accumulations of subangular conglomerate or breccia recall some glacial deposits of modern times. For the most part the stones in the conglomerates are well rounded, sometimes indeed remarkably so, even when they are a foot or more in diameter. The larger blocks are usually angular fragments that have been derived from rocks in the immediate neighbourhood. The smaller rounded stones have often come from some distance; at least it is impossible to discover any near source for them. Bands of red and green clay or marl occur, in which seams and nodules of cornstone may not infrequently be observed. Here and there, too, the sandstones assume a flaggy character, and sometimes pass into fine grey or olive-coloured shales and flagstones. Organic remains occur in some of these grey beds, but are usually absent from the red strata, though in some of the conglomerates teeth, scales, and broken bones of fishes are not uncommon. In the north of Scotland, peculiar very hard calcareous and bituminous flagstones are largely developed, and have yielded the chief part of the remarkable ichthyic fauna of the system. In Scotland, also, contemporaneously erupted diabases, porphyrites, felsites, and tuffs play an important part in the petrography of the Old Red Sandstone, seeing that they attain a thickness in some places of more than 6000 feet, and form important ranges of hills. They point to the existence of extensive volcanic eruptions from numerous vents in the lakes or inland basins in which the sediments were accumulated.

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[1] See *postea*, p. 797. Mr. I. C. Russell in a memoir already cited, on the subaerial decay of rocks and the origin of the red colour of certain formations, concludes that in the majority of cases the ferric oxide was deposited during the subaerial decay of the rocks from which the sediment was derived. *Bull. U.S. Geol. Surv.* No. 52 (1889).

LIFE.—No greater contrast is to be found between the organic contents of any two successive groups of rock than that which is presented by a comparison of the Upper Silurian and Old Red Sandstone systems of Western Europe. The abundant marine fauna of the Ludlow period disappeared from the region. As soon as the red rocks begin, the fossils rapidly die out. Some traces of the aquatic plants that grew in the fresh-water lakes have been detected. An abundant fossil, originally referred to the vegetable kingdom and named *Parka* by Fleming, was afterwards considered to be more probably the egg-packets of the large crustaceans which abounded in these waters. More recently, however, this organism has been carefully studied by Sir J. W. Dawson and Prof. D. P. Penhallow, who have come to the conclusion that it represents what were aquatic plants with creeping stems, linear leaves and sessile sporocarps bearing two kinds of sporangia.[1] On the land that surrounded the lakes or inland seas of the period, there grew the oldest terrestrial vegetation of which more than mere fragments are known. It has been scantily preserved in the ancient lake-bottoms in Europe; more abundantly in Gaspé and New Brunswick. The American localities have yielded to the long-continued researches of Sir J. W. Dawson more than 100 species of land-plants. They are almost all acrogens, lycopods and ferns being largely predominant. Among the distinctive forms the following may be mentioned: *Psilophyton* (Fig. 350), *Arthrostigma*, *Leptophleum*, and *Prototaxites*. Forty-nine ferns include the genera *Palæopteris* (*Cyclopteris*), *Neuropteris*, *Sphenopteris*, and some tree-ferns (*Psaronius*, *Caulopteris*). Lepidodendroid and sigillaroid plants abound, as well as calamites. Higher forms of vegetation are represented by a few conifers (*Dadoxylon*, *Ormoxylon*,[2] &c.) From a locality on Lake Erie, Dawson describes a fragment of what he believes to be dicotyledonous wood, not unlike that of some modern trees—the most ancient fragment of an angiospermous exogen yet discovered. So abundant are the vegetable remains that in some layers they actually form thin seams of coal.

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[1] *Trans. Roy. Soc. Canada*, ix. (1891) sect. iv. pp. 3-16.

[2] *Mem. Geol. Survey Canada*, 1871; *op. cit.* 1873. *Q. J. Geol. Soc.* 1881, p. 299. 'Acadian Geology,' 2nd edition. *Prototaxites*, included by Dawson among the Coniferæ, is relegated by Mr. Carruthers to the Algæ under the name of *Nematophycus*—a genus also found in the Upper Silurian rocks of N. Wales. (*Month. Microscopical Journ.* 1872.)

The interest of this flora is heightened by the discovery of the fact that the primeval forests were not without the hum of insect life. The most ancient known relics of insect forms have been recovered from the Devonian strata of New Brunswick.[1] They include both orthopterous and neuropterous wings, and have been regarded by Mr. Scudder of Boston as combining a remarkable union of characters now found in distinct orders of insects. In one fragment he observed a structure which he could only compare to the stridulating organ of some male *Orthoptera.* Another wing indicates the existence of a gigantic *Ephemera,* with a spread of wing extending to five inches The continued existence of scorpions during this period has been established by the discovery of two genera (*Palæophoneus* and *Proscorpius*) in the Lower Helderberg rocks of New York.

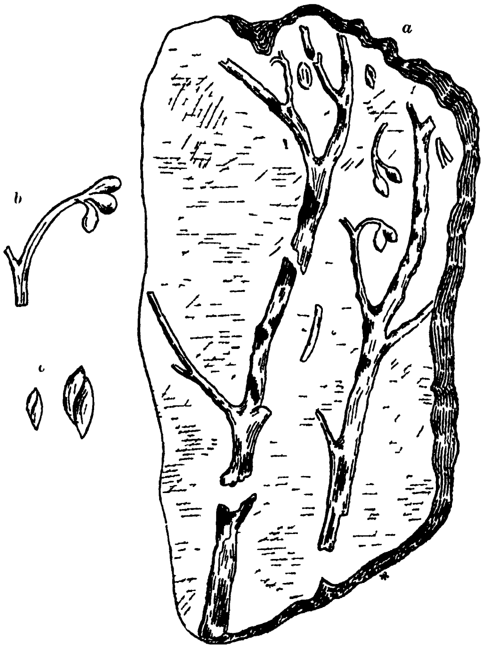

Fig 350 —Psilophyton robustum, Dawson Lower Old Red Sandstone, Perthshire
Drawn by Mr R Kidston
a specimen of the plant ½ nat size, *b*, fructification, *c*, empty spore cases

The existence of myriapods in the forests of this ancient period has been shown by Mr. B. N. Peach, who finds that the so-called *Kampecaris,* previously regarded as a larval form of isopod crustacean, really contains two genera of chilognathous myriapods differing from other

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[1] For a synopsis of all known species of fossil insects up to the year 1890, see *Bull. U.S. Geol. Surv.* No. 71, 1891.

known forms, fossil and recent, in their less differentiated structure, each body segment being separate, and supplied with only one pair of walking legs.[1] There were also pulmoniferous shells, of which one species (*Strophites grandæva*, Dawson) occurs in the plant-beds' of St. John, New Brunswick.

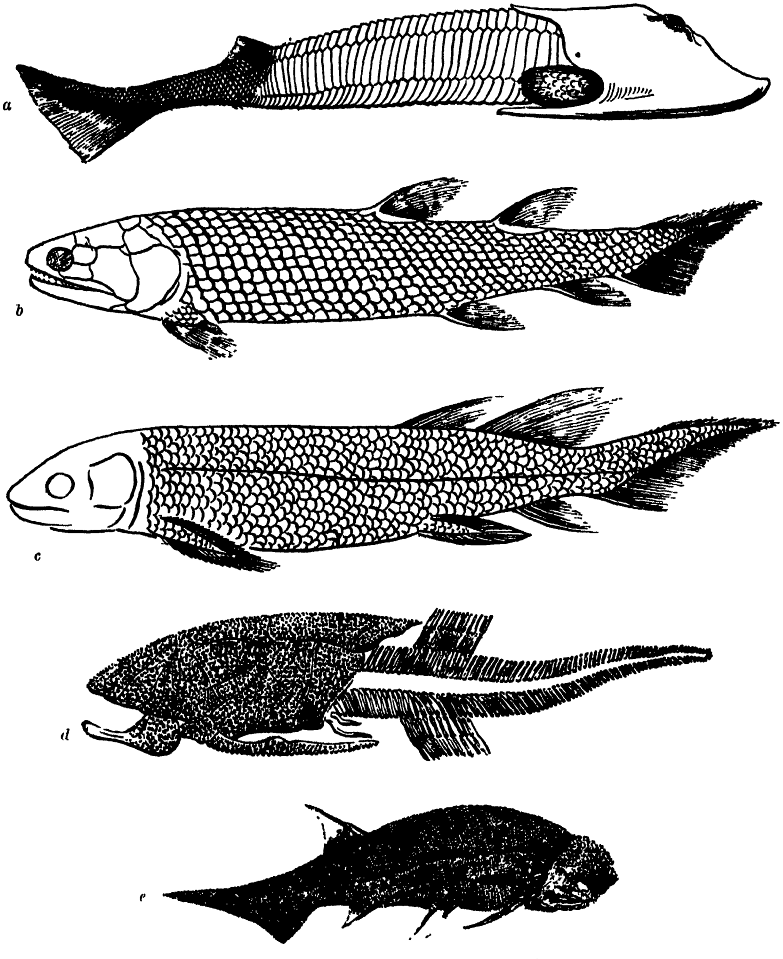

Fig. 851.—Lower Old Red Sandstone Fishes.

a, Cephalaspis Lyelli, Ag. (side view), restored by Professor Ray Lankester; *b*, Osteolepis microlepidotus, Sedgw. and Murch., restored by Dr. Traquair; *c*, Dipterus Valenciennesii, Sedgw. and Murch., from a sketch by Dr. Traquair; *d*, Coccosteus decipiens, Ag.; *e*, Mesacanthus (Acanthodes) Mitchelli, Eg., Forfarshire, from a sketch by Mr. B. N. Peach.

The water-basins of the Old Red Sandstone might be supposed to have been, on the whole, singularly devoid of life; for remains of it have been but meagrely preserved. Nevertheless, in some basins at least (Caithness, Moray Firth), it must have been exceedingly abundant, as is shown by the extraordinary profusion of the fossils. The fauna consists almost wholly of fishes (Figs. 351, 352). Among these the *Pteraspis* survived for a while from Upper Silurian times. With it there lived other forms (*Scaphaspis*, *Holaspis*) and genera of the allied family of the Cephalaspidæ. The ancient order of Dipnoi which still survives in a few forms in some African and Australian rivers (*Protopterus*, *Ceratodus*), was represented in the lakes of the Lower Old Red Sandstone by the abundant *Dipterus*, and in those of the Upper by *Phaneropleuron*. But the ganoids were the most varied order in these waters, being represented by a number of families. Besides those which lingered on from the Upper Silurian period there now appeared the striking group of the Asterolepids of which *Asterolepis* and *Pterichthys* (Fig. 352), are characteristic genera. *Bothriolepis* appears to be confined to the Upper Old Red Sandstone, where it sometimes occurs with other genera crowded together on the surfaces of the layers of stone, as if the fishes had been killed suddenly and had been covered over with sediment where they died. The family of the Coccosteids includes the type genus *Coccosteus* and the gigantic *Homosteus* (*Asterolepis*). This latter form appears to have been the largest fish of the period in the European area, its massive cuirass-like head-shield sometimes measuring twenty inches in length by sixteen in breadth. The sub-order of Acanthodians, marked by their strong fin-spines, attained a great development in the waters of this period; among their genera are *Mesacanthus* (*Acanthodes*), *Cheiracanthus*, *Ischnacanthus* (*Diplacanthus*), *Rhadinacanthus*. The sub-order *Crossopterygidæ*, so remarkable for the central scaly lobe of their fins, and represented at the present time by *Polypterus*, swarmed in the waters, some of the most characteristic genera being *Tristichopterus*, *Gyroptichius*, *Glyptolepis*, *Osteolepis*, *Thursius*, and *Diplopterus* which are found in the Lower Old Red Sandstone of Scotland, and *Holoptychius* which is a characteristic fish of the Upper division of the system. Of the sturgeon tribe there were some small representatives belonging to the genus *Cheirolepis*.[1] The *Dinichthys* already referred to as occurring in the Devonian rocks of North America was probably one of the largest and most formidable of these early fishes. Its head alone encased in strong plates attained a length of 3 feet, and was armed with a powerful apparatus of teeth.

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[1] *Proc. Phys. Soc. Edin.* vii. (1882) p. 179.

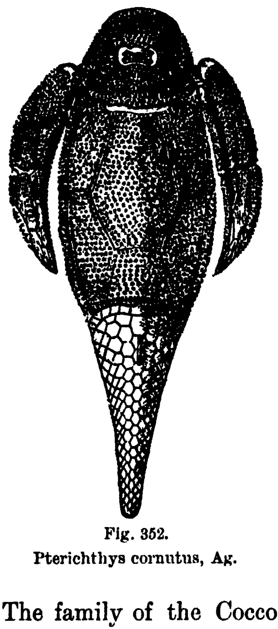

Fig. 352.
Pterichthys cornutus, Ag.

A few eurypterids occur, especially of the genera *Eurypterus* and *Pterygotus* (Fig. 348). The species of the former are small, but one of the latter, *P. anglicus* is found in Scotland, which must have had a length of five or six feet.

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[1] Traquair, *Geol. Mag.* 1888, p. 507. M. Lohest, *Ann. Soc. Géol. Belg.* xv. (1888) p. 112. Whiteaves, *Canad. Nat.* x. Nos. 1, 2 (1881).

§ 2. Local Development.

Britain.—Murchison, who strongly advocated the opinion that the Old Red Sandstone and Devonian rocks represent different geographical conditions of the same period, and who had with satisfaction seen the adoption of the Devonian classification by Continental geologists, endeavoured to trace in the Old Red Sandstone of Britain a threefold division, like that which had been accepted for the Devonian system. He accordingly arranged the formations as in the subjoined table:—

Old Red Sandstone as classified by Murchison.	Upper.	Yellow and red sandstones and conglomerates (*Pterichthys major, Holoptychius nobilissimus*, &c.) = Dura Den beds.
	Middle.	Grey and blue calcareous and bituminous flagstones, limestones, and red sandstones and conglomerates (*Dipterus, Osteolepis, Asterolepis, Acanthodes, Pterichthys*, &c.) = Caithness flags.
	Lower.	Red and purple sandstones, grey sandy flagstones, and coarse conglomerates (*Cephalaspis, Pteraspis, Pterygotus*) = Arbroath flags.

It is important to observe that in no district can these three subdivisions be found together, and that the so-called "middle" formation occurs only in one region—the north of Scotland. The classification, therefore, does not rest upon any actually ascertained stratigraphical sequence, but on an inference from the organic remains. The value of this inference will be estimated a little farther on. All that can be affirmed from the stratigraphical evidence of any district in Britain is that a great physical and palæontological break can generally be traced in the Old Red Sandstone, dividing it into two completely distinct series.[1]

As a whole, the Old Red Sandstone, where its strata are really red, is, like other masses of red deposits, singularly barren of organic remains. As above remarked, the physical conditions under which the precipitation of iron oxide took place are not easily explained. They were evidently unfavourable for the development of animal life in the same waters. Sir A. C. Ramsay has connected the occurrence of such red formations with the existence of salt lakes, from the bitter waters of which not only iron oxide but often rock-salt, magnesian limestone, and gypsum were thrown down.[2] He points also to the presence of land-plants, footprints of amphibia, and other indications of terrestrial surfaces, while truly marine organisms are either found in a stunted condition or are absent altogether. Where the strata of the Old Red Sandstone, losing their red colour and ferruginous character, assume grey or yellow tints and pass into a calcareous or argillaceous condition, they not infrequently become fossiliferous. At the same time, it is worthy of remark that the red conglomerates, which might be supposed little likely to contain organic remains, are occasionally found to be full of detached scales, plates, and bones of fishes.

The Old Red Sandstone of Britain, according to the author's researches, consists of two subdivisions. the lower of which passes down conformably into the Upper Silurian deposits, the upper shading off in the same manner into the base of the Carboniferous system, while they are separated from each other by an unconformability.

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[1] *Q. J. Geol. Soc.* vol. xviii. (1860) p. 312.

[2] Professor Gosselet contends that the precipitation of iron might quite well have taken place in the sea, and he cites the case of the Devonian basin of Dinant, where the same beds are in one part red and barren of organic remains, and in another part of the same area are of the usual colours, and are full of marine fossils. But the red colour of the Old Red Sandstone is general, and is accompanied with other proofs of isolation in the basins of deposit (see p. 792).

1. LOWER.—Red sandstones, conglomerates, flagstones, and associated igneous rocks, passing in some places conformably down into Upper Silurian formations, elsewhere resting unconformably on Dalradian or other older rocks—*Dipterus*, *Coccosteus*, *Cephalaspis*, *Pterygotus*, &c.

In a memoir on the Old Red Sandstone of Western Europe, the author has proposed short names for the different detached basins in which the Lower Old Red Sandstone was accumulated.[1] The most southerly of these (the Welsh Lake) lies in the Silurian region extending from Shropshire into South Wales. Here the uppermost parts of the Silurian system graduate into red strata, not less than 10,000 feet thick, which in turn pass up conformably into the base of the Carboniferous system. This vast accumulation of red rocks consists in its lower portions of red and green shales and flagstones, with some white sandstones and thin cornstones; in the central and chief division, of red and green spotted sandy marls and clays, with red sandstones and cornstones; in the higher parts, of grey. red, chocolate-coloured, and yellow sandstones, with bands of conglomerate. No unconformability has yet been proved in any part of this series of rocks, though, from the observations of De la Beche and Jukes, it may be suspected that the higher strata, which graduate upwards into the Carboniferous formations, are separated from the underlying portions of the Old Red Sandstone by a distinct discordance.[2]

Although, as a whole, barren of organic remains, these red rocks have here and there, more particularly in the calcareous zones, yielded fragments of fishes and crustaceans. In their lower and central portions remains of the fishes *Cephalaspis*, *Didymaspis*, *Scaphaspis*, *Pteraspis*, and *Cyathaspis*, have been found, together with crustaceans of the genera *Stylonurus*, *Pterygotus*, *Prearcturus*, and obscure traces of plants. The upper yellow and red sandstones contain none of the cephalaspid fishes, which are there replaced by *Pterichthys* and *Holoptychius*, associated with distinct impressions of land-plants. In some of the higher parts of the Old Red Sandstone of South Wales and Shropshire, *Serpula* and *Conularia* occur, but these are exceptional cases, and point to the advent of the Carboniferous marine fauna, which doubtless existed outside the British area before it spread over the site of the Old Red Sandstone basins (see p. 801).

It is in Scotland[3] that the Old Red Sandstone shows the most complete and varied development, alike in physical structure and in organic contents. Throughout that country the system is found to consist of two well-marked groups of strata, separated from each other by a strong unconformability and a complete break in the succession of organic remains. Each subdivision occurs in distinct basins of deposit. The most important basin of the Lower Old Red Sandstone occupies the central valley, between the base of the Highland mountains and the Uplands of the southern counties (Lake Caledonia). On the north-east, it presents a series of noble cliff-sections along the coast-line from Stonehaven to the mouth of the Tay. On the south-west it ranges by the island of Arran and the south of Cantyre across St. George's Channel into Ireland, where it runs almost to the western seaboard, flanked on the north, as in Scotland, by hills of crystalline rocks, and on the south chiefly by a Silurian belt. In this basin abundant volcanic action manifested itself across the whole breadth of Scotland and in the north of Ireland. Another distinct and still larger basin (Lake Orcadie) of the lower subdivision lies on the north side of the Highlands, but only a portion of it emerges above the sea in the north of Scotland. Skirting the slopes of the mountains along the Moray Firth and the east of Ross and Sutherland, it stretches through Caithness and the Orkney Islands as far as the south of the Shetland group, and may possibly have been at one time continued as far as the Sognefjord and Dalsfjord in Norway, where red conglomerates like those of the north of Scotland occur. There is even reason to infer that it may have ranged eastwards into Russia, for, as already stated, some of its most characteristic organisms are found also among the Devonian strata of that country. Several distinct contemporaneous volcanic centres have been detected in this basin. A third minor area of the Lower Old Red Sandstone (Lake Cheviot) lay on the south side of the Southern Uplands, over the east of Berwickshire and the north of Northumberland, including the area of the Cheviot Hills, where a copious volcanic series has been preserved. A fourth (Lake of Lorne) occupied a basin on the flanks of the south-west Highlands, which is now partly marked by the terraced volcanic hills of Lorne. There is sufficient diversity of lithological and palæontological characters to show that these several areas were on the whole distinct basins, separated both from each other and from the sea. The interval between the Lower and Upper Old Red Sandstone was so protracted, and the geographical changes accomplished during it were so extensive, that the basins in which the late parts of the system were deposited only partially correspond with those of the older lakes.

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[1] *Trans. Roy. Soc. Edin.* vol. xxviii. (1879).

[2] De la Beche, *Mem. Geol. Surv.* vol. i. (1846) p. 50. J. B. Jukes, 'Letters, &c.' (1871) p. 508; letter to A. C. Ramsay, dated 1857. Symonds, 'Records of the Rocks' (1872); Hughes, *Brit. Assoc. Rep.* (1875) sects. p. 70.

[3] See Agassiz, 'Poissons du Vieux Grès Rouge,' Hugh Miller's 'Old Red Sandstone,' and 'Footprints of the Creator'; J. Anderson's 'Dura Den'; *Explanations Geol. Surv. Scotland*, sheets 14, 15, 23, 24, 32, 33, 34; author's memoir cited on previous page, and papers referred to in subsequent notes.

In the central basin, or Lake Caledonia, both divisions of the Old Red Sandstone are typically seen. The lower series of deposits, attaining a maximum depth of perhaps 20,000 feet, everywhere presents traces of shallow-water conditions. The accumulation of so great a thickness of sediment can only be explained on the supposition that the subterranean movements, which at first ridged up the Silurian sea-floor into land, enclosing separate basins, continued to deepen these basins, until eventually, enormous masses of sediment had slowly gathered in them. This massive series of deposits passes down conformably in Lanarkshire into Upper Silurian rocks; elsewhere its base is concealed by later formations, or by the unconformability with which different horizons rest upon the older rocks. Covered unconformably by every rock younger than itself, it consists of reddish-brown or chocolate-coloured, grey, and yellow sandstones, red shales, grey flagstones, coarse conglomerates, with occasional bands of limestone and cornstone. The grey flagstones and thin grey and olive shales and "calmstones" are almost confined to Forfarshire, in the north-east part of the basin, and are known as the "Arbroath flags." One of the most marked lithological features in this central Scottish basin is the occurrence in it of extensive masses of interbedded volcanic rocks. These, consisting of diabases, porphyrites, felsites, and tuffs, attain a thickness of more than 6000 feet, and form important chains of hills, as in the Pentland, Ochil, and Sidlaw ranges. They lie several thousand feet above the base of the system, and are regularly interstratified with bands of the ordinary sedimentary strata. They point to the outburst of numerous volcanic vents along the lake or inland sea in which the Lower Old Red Sandstone of central Scotland was laid down; and their disposition shows that the vents ranged themselves in lines or linear groups, parallel with the general trend of the great central valley. The fact that the igneous rocks are succeeded by thousands of feet of sandstones, shales, and conglomerates, without any intercalation of lava or tuff, proves that the volcanic episode in the history of the lake came to a close long before the lake itself disappeared.[1] As a rule, the deposits of this basin are singularly unfossiliferous, though some portions of them, particularly in the Forfarshire (Arbroath) flagstone group, have proved rich in remains of crustaceans and fish. Nine or more species of crustaceans have been obtained, chiefly eurypterids, but including one or two phyllopods. The large pterygotus (*P. anglicus*) is especially characteristic, and must have attained a great size, for some of the individuals indicate a length of 6 feet, with a breadth of 1½ feet. There occur also a smaller species (*P. minor*), two *Eurypteri*, and three species of *Stylonurus*. Upwards of twenty species of fishes have been obtained, chiefly from the Arbroath flags, belonging to the sub-orders *Acanthodidæ* and *Ostracostei* (Fig. 351). One of the most abundant forms is the little *Mesacanthus* (*Acanthodes*) *Mitchelli*. Another common fish is *Ischnacanthus* (*Diplacanthus*) *gracilis*. There occur also *Climatius scutiger*, *C. reticulatus*, *C. uncinatus*, *C. Macnicoli*, *C. grandis*, *C. gracilis*, *Parexus incurvus*, *Cephalaspis Lyellii*, and *Pteraspis Mitchelli*. Some of the sandstones and shales are crowded with indistinctly preserved vegetation, occasionally in sufficient quantity to form thin laminæ of coal. The egg-like impressions known as *Parka decipiens* and referred to on p. 793, also abound in some layers. In Forfarshire, the surfaces of the shaly flagstones are now and then covered with linear grass-like plants, like the sedgy vegetation of a lake or marsh. In Perthshire, certain layers occur, chiefly made up of compressed stems of *Psilophyton* (Fig. 350). The adjoining land was doubtless clothed with a flora in large measure lycopodiaceous.

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[1] Presidential Address, *Quart. Journ. Geol. Soc.* 1882, p. 62 *seq.*

The Old Red Sandstone of the northern basin (Lake Orcadie) is typically developed in Caithness, where it consists chiefly of the well-known dark-grey bituminous and calcareous flagstones of commerce. It rests unconformably upon various crystalline schists, granites, &c., and must have been deposited on the very uneven bottom of a sinking basin, seeing that occasionally even some of the higher platforms are found resting against the more ancient rocks. The lower zones consist of red sandstones and conglomerates, which graduate upward into the flagstones. Other red sandstones, however, supervene in the higher parts of the system. The total depth of the series in Caithness has been estimated at upwards of 16,000 feet. Murchison was the first to attempt the correlation of the Caithness flagstones with the Old Red Sandstone of the rest of Britain. Founding upon the absence from these northern rocks of the cephalaspidean fishes characteristic of the admitted Lower Old Red Sandstone in the south of Scotland and in Wales and Shropshire, upon the presence of numerous genera of fishes not known to occur elsewhere in the true Lower Old Red Sandstone, and upon the discovery of a *Pterygotus* in the basement red sandy group of strata, he concluded that the massive flagstone series of Caithness could not be classed with the Lower Old Red Sandstone, but must be of younger date. He supposed the red sandstones, conglomerates, and shales at the base, with their *Pterygotus*, to represent the true Lower Old Red Sandstone, while the great flagstone series with its distinctive fishes was made into a middle division answering in some of its ichthyolitic contents to the Middle Devonian rocks of the Continent. This view was accepted by geologists. I have, however, endeavoured to show that the Caithness flagstones belong to the Lower Old Red Sandstone, and that there is no evidence of the existence of any middle division. It appears to me that the discrepance in organic contents between the Caithness and the Arbroath flags is by no means so strong as Murchison supposed, but that several species are common to both. In particular, I find that the characteristically Lower Old Red Sandstone and Upper Silurian crustacean genus *Pterygotus* occurs, not merely in the basement zone of the Caithness flags, but also high up in the series. The genera *Acanthodes* (*Mesacanthus*) and *Diplacanthus* (*Ischnacanthus*) appear both in Caithness and in Forfarshire. *Parexus incurvus* occurs in the northern as well as the southern basin. The admitted palæontological distinctions are probably not greater than the striking lithological differences between the strata of the two regions would account for, or than the contrast between the ichthyic faunas of adjacent but disconnected water-basins at the present time.

More than sixty species of fishes have been obtained from the Old Red Sandstone of the north of Scotland. Among these, the genera *Acanthodes*, *Asterolepis*, *Cheiracanthus*, *Cheirolepis*, *Coccosteus*, *Diplacanthus*, *Diplopterus*, *Dipterus*, *Glyptolepis*, *Osteolepis*, and *Pterichthys* are specially characteristic. Some of the shales are crowded with the little phyllopod crustacean *Estheria membranacea*. Land-plants abound, especially in the higher groups of the flagstones, where forms of *Psilophyton*, *Lepidodendron*, *Stigmaria*, *Sigillaria*, *Calamites*, and *Cyclopteris*, as well as other genera, occur. In the Shetland Islands, traces of abundant contemporaneous volcanic rocks have been observed.[1] These, with the exception of two trifling examples in the region of the Moray Firth, are the only known instances of volcanic action in the Lower Old Red Sandstone of Lake Orcadie. In the other two Scottish basins, those of the Cheviot Hills[2] and of Lorne,[3] volcanic action long continued vigorous, and produced thick piles of lava, like those of Lake Caledonia.

2. UPPER.—This division consists of yellow and red sandstones, conglomerates, marls, &c., passing up conformably into the base of the Carboniferous system, and resting unconformably on the Lower Old Red Sandstone and every older formation. Among its distinctive fossils are *Holoptychius*, *Bothriolepis* (*Pterichthys*) *major*, &c.

Below the Carboniferous system there occur in Scotland certain red sandstones, deep-red clays or marls, conglomerates, and breccias, the sandstones passing into yellow or even white. These strata, wherever their stratigraphical relations can be distinctly traced, lie unconformably upon every formation older than themselves, including the Lower Old Red Sandstone, while, on the other hand, they pass up conformably into the Carboniferous rocks above. As already remarked, they were deposited in basins, which only partially corresponded with those wherein the Lower Old Red Sandstone had been laid down. Studied from the side of the underlying formations, they seem naturally to form part of the Old Red Sandstone, since they agree with it in general lithological character, and also in containing some distinctively Old Red Sandstone genera of fishes, such as *Pterichthys* and *Holoptychius*; though, approached from the upper or Carboniferous direction, they might rather be assumed as the natural sandy base of that system into which they insensibly graduate. On the whole, they are remarkably barren of organic remains, though in some localities (Dura Den in Fife, Lauderdale) they have yielded a number of genera and species of fishes, crowded profusely through the pale sandstone, as if the individuals had been suddenly killed and rapidly covered over with sediment (see p. 648). Among the characteristic organisms of the Scottish Upper Old Red Sandstone are *Bothriolepis* (*Pterichthys*) *major*, *Holoptychius nobilissimus*, *H. Andersoni*, *Glyptopomus*, *Glyptolæmus* and *Phaneropleuron*.

In the Upper Old Red Sandstone of the Firth of Clyde, *Bothriolepis* (*Pterichthys*) *major* and *Holoptychius* occur at the Heads of Ayr, while a band of marine limestone, lying in the red sandstone series in Arran, is crowded with ordinary Carboniferous Limestone shells, such as *Productus giganteus*, *P. semireticulatus*, *P. punctatus*, *Chonetes hardrensis*, *Spirifer lineatus*, &c. These fossils are absent from the great series of red sandstones overlying the limestone, and do not reappear till we reach the limestones in the Lower Carboniferous series; yet the organisms must have been living during all that long interval outside of the Upper Old Red Sandstone area (p. 828). Not only so, but they must have been in existence long before the formation of the thick Arran limestone, though it was only during the comparatively brief interval represented by that limestone that geographical changes permitted them to enter the Old Red Sandstone basin and settle for a while on its floor. The higher parts of the Upper Old Red Sandstone seem thus to have been contemporaneous with a Carboniferous Limestone fauna which, having appeared beyond the British area, was ready to spread over it as soon as the conditions became favourable for the invasion. It is, of course, obvious that such an abundant and varied fauna as that of the Carboniferous Limestone cannot have come suddenly into existence at the period marked by the base of the limestone. It must have had a long previous existence outside the present area of the deposit.

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[1] *Trans. Roy. Soc. Edin.* xxviii. (1878) p. 345. Presidential Address, *Quart. Journ. Geol. Soc.* xlviii. (1892) p. 94. Peach and Horne, *Trans. Roy. Soc. Edinr.* xxxii. (1884) p. 359.

[2] C. T. Clough, 'Cheviot Hills,' *Geol. Surv. Mem.* Sheet 108 N.E. (1888); J. J. H. Teall, *Geol. Mag.* 1883.

[3] Presidential Address, *Quart. Journ. Geol. Soc.* xlviii. (1892) p. 95.

In the north of Scotland, on the Lowlands bordering the Moray Firth, and again in the island of Hoy, one of the Orkney group, yellow and red sandstones (with interbedded diabase and tuff), containing characteristic Upper Old Red Sandstone fishes, lie unconformably upon the Caithness flags.[1] In these northern tracts, the same relation is thus traceable as in the central counties, between the two divisions of the system.

Turning southward across the border districts into the north of England, we find the red sandstones and conglomerates of the Upper Old Red Sandstone lying unconformably on Silurian rocks and Lower Old Red Sandstone. Some of the brecciated conglomerates have much resemblance to glacial detritus, and it was suggested by Ramsay that they have been connected with contemporaneous ice-action.[2] Such are the breccias of the Lammermuir Hills, and those which show themselves here and there from under the overlying mass of Carboniferous strata that flanks the Silurian hills of Cumberland and Westmoreland. Red conglomerates and sandstones appear interruptedly at the base of the Carboniferous rocks, even as far as Flintshire and Anglesey. They are commonly classed as Old Red Sandstone, but merely from their position and lithological character. No organic remains have been found in them. They may therefore, in part at least, belong to the Carboniferous system, having been deposited on different successive horizons during the gradual depression of the land. In Devonshire, at Barnstaple, Pilton, Marwood, and Baggy Point, certain sandstones, shales, and limestones (already referred to in the account of the Devonian rocks) graduate upward into the base of the Carboniferous system, and appear to represent the Upper Old Red Sandstone of the rest of Britain. They contain land-plants and also many marine fossils, some of which are common Carboniferous forms. They thus indicate a transition into the geographical conditions of the Carboniferous period, as is still more clearly illustrated by the corresponding strata in Scotland.

The Old Red Sandstone attains a great development in the south and south-west of Ireland. The thick "Dingle-Beds" and "Glengariff grits" pass down into Upper Silurian strata, and no doubt represent the Lower Old Red Sandstone of Scotland. They are succeeded in Kerry by red sandstones which cover them unconformably, and resemble the ordinary Upper Old Red Sandstone of Scotland. In Cork and the south-east of Ireland they are followed by the pale sandstones and shaly flagstones known as the "Kiltorcan beds," with apparently a perfect conformability. The Kiltorcan beds (which pass up conformably into the Carboniferous Slate) have yielded a few fishes (*Bothriolepis*, *Coccosteus*, *Pterichthys*, *Glyptolepis*), some crustaceans (*Belinurus*, *Pterygotus*), a fresh-water lamellibranch (*Anodonta Jukesii*), and a number of ferns and other land-plants (*Palæopteris*, *Sphenopteris*, *Sagenaria* (*Cyclostigma*), *Knorria*.[3]

Norway, &c.—On the continent of Europe the Old Red Sandstone type can hardly be said to occur. Some outliers of red sandstone and conglomerate (p. 799) in northern and western Norway reach a thickness of 1000 to 1200 feet. Near Christiania, they follow the Silurian strata like the Old Red Sandstone, but as yet have yielded no fossils, so that, as they pass up into no younger formation, their geological horizon cannot be certainly fixed. The Devonian rocks of Russia have been above referred to as presenting a union of the two types of this part of the geological series. The extension of the land of the Old Red Sandstone period, with its characteristic flora, far north within the Arctic circle is indicated by the discoveries made at Bear Island (lat. 70° 30′ N.) between the coast of Norway and Spitzbergen. Certain seams of coal and coaly shale occur at that locality, underlying beds of Carboniferous Limestone and overlying some yellow dolomite, calcareous shale, and red shales. They have been assigned by Heer to the Carboniferous series, but are regarded by Dawson as unquestionably Devonian. They may be correlated with the Upper Old Red Sandstone of Britain. Heer enumerates eighteen species; only three are peculiar to the locality, while among the others are some widely-diffused forms: *Calamites radiatus* (*transitionis*), *Palæopteris roemeriana*, *Sphenopteris Schimperi*, *Cardiopteris frondosa*, *Lepidodendron veltheimianum* and three other species, *Knorria imbricata*, and *Sagenaria* (*Cyclostigma*) *kiltorkensis*.[1] In Spitzbergen itself, according to the researches of Nathorst, the so-called "Heckla-Hook formation" contains a large assemblage of fish-remains, shells, and plants, which prove it to be the equivalent of part of the Scottish Old Red Sandstone.

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[1] *Trans. Roy. Soc. Edin.* xxviii. (1878) p. 405; *Quart. Journ. Geol. Soc.* xlviii. (1892) Presidential Address, p. 100.

[2] The examples of supposed glacial striæ in the pebbles in these breccias may be merely frictional markings connected with faults or internal movements of the rocks. But the forms of the pebbles, their moraine-like unstratified or rudely-stratified accumulation, and the occurrence of aggregated lumps of breccia in the midst of fine sandstone strongly remind one of the familiar features of true glacial deposits. Compare H. Reusch, on similar evidence from the Palæozoic rocks of Norway, *Norges Geol. Undersög. Aarbog.* 1891.

[3] Prof. Hull, *Q. J. Geol. Soc.* xxxv. xxxvi.; *Trans. Roy. Dublin Soc.* (new ser.) i. p. 135, 1880; *Explanations of the Geol. Survey, Ireland*, sheets 167, &c., 187, &c.; J. Nolan, *Q. J. Geol. Soc.* 1880, p. 529; Kinahan, *Trans. Geol. Soc. Edin.* 1882, p. 152. A recent personal examination has convinced me that the south of Ireland formed another of the basins in which the Lower Old Red Sandstone was accumulated.

North America.—It is interesting to observe that in North America representatives occur of the two divergent Devonian and Old Red Sandstone types of Europe. The American Devonian facies has already been referred to. On the eastern side of the ancient pre-Cambrian and Silurian ridge, which, stretching southwards from Canada, separated in early Palæozoic time the great interior basin from the Atlantic slopes, we find the Devonian rocks of New York, Pennsylvania, and the interior represented in New Brunswick and Nova Scotia by a totally different series of deposits. The contrast strikingly recalls that presented by the Old Red Sandstone of the north of Scotland and the Devonian rocks of North Germany. On the south side of the St. Lawrence, the coast of Gaspé shows rocks of the so-called "Quebec group" unconformably overlain by grey limestones with green and red shales, attaining, according to Logan, a total thickness of about 2000 feet,[2] and in some bands replete with Upper Silurian fossils. They are conformably followed by a vast arenaceous series of deposits termed the Gaspé Sandstones, to which the careful measurements of Logan and his colleagues of the Canadian Geological Survey assign a depth of 7036 feet. This formation consists of grey and drab-coloured sandstones, with occasional grey shales and bands of massive conglomerate. Similar rocks reappear along the southern coast of New Brunswick, where they attain a depth of 9500 feet, and again on the opposite side of the Bay of Fundy. The researches of Sir J. W. Dawson, already referred to, have made known the remarkable flora of these rocks. Some of the same plants have been met with in the Devonian rocks to the west of the Archæan ridge, so that there can be little doubt of the contemporaneity of the deposits on the two sides. Besides the abundant vegetation, a few traces of the fauna of the period have been recovered from the Old Red Sandstone. Among them are the remains of several small crustaceans, including a minute shrimp-like *Eurypterus*, and the more highly organised *Amphipeltis*, with the snail (*Strophites*) referred to on p. 795. That the sea had at least occasional access to the inland basins into which the abundant terrestrial vegetation was washed, is proved by the occurrence of marine organisms, such as a small annelid (*Spirorbis*) adhering to the leaves of the plants, and (in Gaspé and Nova Scotia) by the occasional appearance of brachiopods, especially *Lingula*, *Spirifer*, and *Chonetes*.[3]

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[1] Heer, *Q. J. Geol. Soc.* xxviii. p. 161. Dawson, *op. cit.* xxix. p. 24.

[2] 'Geology of Canada,' p. 393.

[3] Dawson's 'Acadian Geology,' chaps. xxi. and xxii.

Section iv. Carboniferous.

§ 1. General Characters.

This great system of rocks has received its name from the seams of coal which form one of its distinguishing characters in most parts of the world. Both in Europe and America it may be seen passing down conformly into the Devonian and Old Red Sandstone. So insensible indeed is the gradation in many consecutive sections where the two systems join each other that no sharp line can there be drawn between them. This stratigraphical passage is likewise in many places associated with a corresponding commingling of organic remains, either by the ascent of undoubted Devonian species into the lower parts of the Carboniferous series, or by the appearance in the Upper Devonian beds of species which attained their maximum development in Carboniferous times. Hence there can be no doubt as to the true place of the Carboniferous system in the geological record. In some places, however, the higher members of this system are found resting unconformably upon Devonian or older rocks, so that local disturbances of considerable magnitude occurred before or at the commencement of the Carboniferous period. It is deserving of notice that Carboniferous rocks are very generally arranged in basin-shaped areas, many of which have been wholly or partially overspread unconformably by later formations. This disposition, so well seen in Europe, and particularly in the central and western half of the continent, has in some cases been caused merely by the plication and subsequent extensive denudation of what were originally wide continuous sheets of rock, as may be observed in the British Isles. But the remarkable small scattered coal-basins of France and central Germany were probably from the first isolated areas of deposit, though they have suffered, in some cases very greatly, from subsequent plication and denudation. In Russia, and still more in China and western North America, Carboniferous rocks cover thousands of square miles in horizontal or only very gently undulating sheets.

ROCKS.—The materials of which the Carboniferous system is built up differ considerably in different regions; but two facies of sedimentation have a wide development. In one of these, the marine type, limestones form the prevailing rocks, and are often visibly made up of organic remains, chiefly encrinites, corals, foraminifera, and mollusks. According to Dupont's researches in the Carboniferous Limestone of Belgium there are two main types of limestone: (1) the massive limestones formed by reef-building corals and coralloid animals, and disposed in fringing reefs or dispersed atolls, according to their nearness to or distance from the coast of the time; and (2) the detritic limestones, consisting either of an aggregation of crinoid stems or of coral-débris, and often stretching in extensive sheets like sandstone or shale.[1] The limestones of both types assume a compact homogeneous character, with black, grey, white, or mottled colours, and are occasionally largely quarried as marble. Local developments of oolitic structure occur among them. They also assume in some places a yellowish, dull, finely granular aspect and more or less dolomitic composition. They occur in beds, sometimes as in central England, Ireland, and Belgium, piled over each other for a depth of hundreds of feet, and in Utah for several thousand feet, with little or no intercalation of other material than limestone. The limestones frequently contain irregular nodules of a white, grey, or black flinty chert (phtanite), which, presenting a close resemblance to the flints of the chalk, occur in certain beds or layers of rock, sometimes in numbers sufficient to form of themselves tolerably distinct strata.[1] These concretions are associated with the organisms of the rock, some of which, completely silicified and beautifully preserved, may be found imbedded in the chert. Dolomite, usually of a dull yellowish colour, granular texture, and rough feel, occurs both in beds regularly interstratified with the limestones and also in broad wall-like masses running through the limestones. In the latter cases, it is evident that the limestone has been changed into dolomite along lines of joint; in the former, the dolomite may be due to contemporaneous alteration of the original calcareous deposit by the magnesian salts of sea-water as already explained (pp. 321, 412). Traced to a distance, the limestones are often found to grow thinner, and to be separated by increasing thicknesses of shale, or to become more and more argillaceous and to pass eventually into shale. The shales, too, are often largely calcareous, and charged with fossils; but in some places assume dark colours, become more thoroughly argillaceous, and contain, besides carbonaceous matter, an impregnation of pyrites or marcasite. Where the marine Carboniferous type dies out, the shales may pass even into coal, associated with sandstones, clays, and ironstones. In Britain, abundant contemporaneous volcanic rocks are preserved in the Carboniferous Limestone series.

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[1] *Bull. Acad. Roy. Belg.* (3) v. 1883, No. 2.

The second facies of sedimentation points to deposit in shallow lagoons, which at first were replenished from the sea, but afterwards appear to have been brackish and then fresh, or in lakes into which coarse and fine detritus as well as vegetation and animal remains were washed from neighbouring land. The most abundant strata of this type are sandstones, which, presenting every gradation of fineness of grain up to pebbly grits, and even (near former shore-lines) conglomerates, are commonly yellow, grey, or white in colour, well-bedded, sometimes micaceous and fissile, sometimes compact; often full of streaks or layers of coaly matter. Besides the existence of pebbly grits and conglomerates pointing to comparatively strong currents of transport, there occur in different parts of the Carboniferous system, scattered pieces and even blocks of granite, gneiss, quartzite, or other durable material which lie imbedded, sometimes singly sometimes in groups, in limestone, sandstone, and in coal. Various explanations have been proposed to account for these erratics, some writers having even suggested the action of drifting ice.[2] The stones were most probably transported by floating plants.

[1] Renard, *op. cit.* (2) xlvi. p. 9.

[2] For remarks on the climate of the Carboniferous period see *postea*, p. 809.

Seaweeds with their rootlets wrapt round loose blocks might easily be torn up and drifted out to sea so as to drop their freight among corals and crinoids living on the bottom. But more usually trees growing on the land would envelop soil and stones among their roots, and if blown down and carried away by storms and floods might bear these with them.[1]

Next in abundance to the sandy sediment came the deposits of mud now forming shales. These occur in seams or bands from less than an inch to many yards in thickness. They are commonly black and carbonaceous, frequently largely charged with pyritous impregnations, sometimes crowded with concretions of clay-ironstone. Coal occurs among these strata in seams varying from less than an inch up to several feet or yards in thickness, but swelling out in some rare examples to 100 feet or more. A coal-seam may consist entirely of one kind of coal. Frequently, however, it contains one or more thin layers or "partings" of shale, the nature or quality of the seam being alike or different on the two sides of the parting. The same seam may be a cannel-coal at one part of a mineral field, an ordinary soft coal at a second, and an ironstone at a third. Moreover, in Britain and other countries, each coal-seam is usually underlain by a bed of fire-clay or shale, through which rootlets branch freely in all directions. These fireclays, as their name denotes, are used for pottery or brick-making. They appear to be the soil on which the plants of the coal grew, and it was doubtless the growth of the vegetation that deprived them of their alkalies and iron, and thus made them industrially valuable. In the small coal-basins of central France the coal is dispersed in banks and isolated veins all through the Carboniferous strata. Clay-ironstone occurs abundantly in some coal-fields, both in the form of concretions (sphærosiderite) and also in distinct layers from less than an inch to eighteen inches or more in thickness. The nodules have generally been formed round some organic object, such as a shell, seed-cone, fern-frond, &c. Many of the ironstone beds likewise abound in organic remains, some of them, like the "mussel-band" ironstone of Scotland, consisting almost wholly of valves of *Anthracosia* or other shell converted into carbonate of iron.

The mode of origin of coal cannot be closely paralleled by any modern formation, and various divergent views have been expressed on the subject. There seem to have been two distinct modes of accumulation, (1) by growth *in situ*, and (2) by drifting from adjacent land. It is possible that in some coal-fields both these processes may have been successively or simultaneously in operation, so that the results are commingled.

1. In those cases where the evidence points to growth *in situ*, the coal-seams have been laid down with tolerable uniformity of thickness and character over considerable areas of ground, and they now appear as regular layers intercalated between sheets of sediment and for the most part rest on fireclay or shale, into which the stigmaria rootlets may fre-

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[1] For accounts of these travelled stones in Carboniferous rocks see especially D. Stur, *Jahrb. Geol. Reichsanst.* xxxv. (1885) p. 613, and the authorities cited by him; also W. S. Gresley, *Geol. Mag.* 1885, p. 553; *Quart. Journ. Geol. Soc.* xliii. (1887) p. 734; V. Ball, *op. cit.* xliv. (1888) p. 371.

quently be seen to ramify as in the position of growth.[1] The nearest analogy to these conditions is probably furnished by cypress swamps[2] or the mangrove swamps alluded to already (p. 481), where masses of arborescent vegetation, with their roots spreading in salt water among marine organisms, grow out into the sea as a belt or fringe on low shores, and form a matted soil which adds to the breadth of the land. The coal-

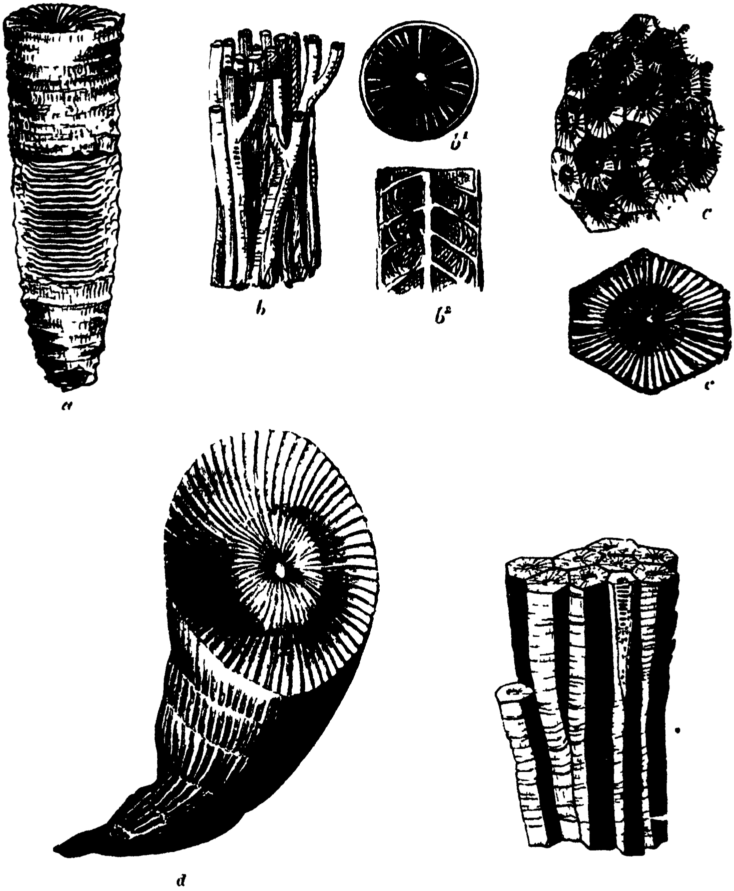

Fig. 353 – Carboniferous Corals.

a, Zaphrentis cylindrica, Scoul.; *b*, Lithostrotion junceum, Flem., b^1, Do. magnified, transverse section, b^2, Do. magnified, longitudinal section; *c*, Lithostrotion Portlocki, Milne Edw., c^1, Do. calyx magnified; *d*, Cyathophyllum Stutchburyi, Milne Edw.; *e*, Lithostrotion basaltiforme, Phill., sp.

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[1] For arguments in support of the view that coal was formed of plants *in situ* see Logan, *Trans. Geol. Soc.* vi. (1842) p. 491. Newberry, *Amer. Journ. Sci.* xxiii. (1857) p. 212, 'Geol. Surv. Ohio,' vol. ii. Geology, p. 125; Gumbel, *Sitzb. Bayer. Akad.* 1883.

[2] For an account of the submerged lands of the Mississippi, see Lyell's 'Second Visit to the United States,' chap. xxxiii.

growths no doubt also flourished in salt water; for such shells as *Aviculopecten* and *Goniatites* are found lying on the coal or in the shales attached to it. Each coal-seam represents the accumulated growth of a period which was limited either by the exhaustion of the soil underneath the vegetation (as may be indicated by the composition of the fire-clays), or by the rate of the intermittent subsidence that affected the whole area of coal-growths. Though the vegetation in these coal-fields may have grown as a whole *in situ*, there may also have been considerable transport of loose leaves, branches, trunks, &c., after storms, and also during times of more rapid subsidence. From the fact that a succession of coal-seams, each representing a former surface of terrestrial vegetation, can be seen in a single coal-field extending through a vertical thickness of 10,000 feet or more, it is clear that the strata of such a field must have been laid down during prolonged and extensive subsidence. It has been assumed that, besides depression, movements in an upward direction were needful to bring the submerged surfaces once more up within the limits of plant growth. But this would involve a prolonged and almost inconceivable sea-saw oscillation; and the assumption is really unnecessary if we suppose that the downward movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting-up of lagoons and the spread of coal-jungles.[1]

2. The researches of Grand' Eury, Fayol, and others in the small coal-basins of central France have shown that in these regions much vegetable matter was washed down from adjacent land.[2] The coal is irregularly distributed among the strata, and it is associated with beds of coarse detritus and other evidence of torrential action. Numerous trunks of calamododendra, sigillariæ, and other trees imbedded in the sandstones and shales vertically and at all angles of inclination bear witness, like the "snags" of the Mississippi, to the currents that transported them. The basins in which the accumulated detritus and vegetation were entombed seem to have been small, but sometimes comparatively deep lakes lying on the surface of the crystalline rocks that formed an uneven land-surface during the Carboniferous period in the heart of France. But there is evidence, even in these basins, of the growth of coal-plants *in situ*, and of the gradual subsidence of the alluvial floors on which they took root. Grand' Eury has shown the existence of tree-trunks with their roots in place on many successive levels, and has further ascertained that these trees, as they were enveloped in sediment, pushed out rootlets at higher levels into the silt that gathered round them.

It would thus appear that no one hypothesis is universally applicable for the explanation of the origin of coal, but that growth on the spot and transport from neighbouring land have both in different regions contemporaneously and at successive periods come into play.

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[1] See a statement of the oscillation theory as far back as 1849 by M. Virlet d'Aoust, *Bull. Soc. Géol. France* (2) vi. p. 616.

[2] For the detrital origin of coal, see Grand' Eury, *Ann. des Mines*, 1882 (i.) pp. 99-[illegible]; *Mém. Soc. Géol. France*, 3e sér. iv. 1887; 'Geol. et Paleontol. du bassin Houiller du [illegible], 1891. Fayol, 'Études sur le Terrain Houiller de Commentry,' part 1. *Bull Soc. [illegible] Min.* sér. 2, vol xv. and Atlas (1887). *Bull. Soc. Géol. France*, 3e sér. xvii. [illegible] Renault, 'Flore Fossile de Commentry,' *Bull. Soc. Hist. Nat. d'Autun* (1891). A. de Lapparent, *Rev. Quest. Scien.* July 1892.

In this place reference may most conveniently be made to the probable climate in which these geological changes took place. The remarkable profusion of the vegetation of the Carboniferous period, not only in the Old World but in the New, suggested the idea that the atmosphere was then much more charged with carbonic acid than it now is. Undoubtedly there has been a continual abstraction of this gas from the atmosphere ever since land-plants began to live on the earth's surface, and it is allowable to infer that the proportion of it in the air in Palæozoic time may have been somewhat greater than now. But the difference could hardly have been serious, otherwise it seems incredible that the numerous insects, labyrinthodonts and other air-breathers, could have existed. Most probably the luxuriance of the flora is rather to be ascribed to the warm moist climate which in Carboniferous times appears to have spread over the globe even into Arctic latitudes. On the other hand, evidence has been adduced to support the view that in spite of the genial temperature indicated by the vegetation there were glaciers even in tropical and sub-tropical regions. Coarse boulder-conglomerates and striated stones have been cited from various parts of India, South Africa, and Eastern Australia, as evidence of ice-action. There appears, however, to be some element of doubt as to the interpretation of the facts adduced. It may be matter for consideration whether the boulder-beds could not be accumulated by torrential waters, and whether the striated surfaces on the stones might not have been produced by internal movements in the rocks, like slickensides (p. 526).[1]

LIFE.—Each of the two facies of sedimentation above described has its own characteristic organic types, the one series of strata presenting us chiefly with the fauna of the sea, the other mainly with the flora of the land. The marine fauna is specially rich in crinoids, corals, and brachiopods, which of themselves constitute entire beds of limestone. Among the lower forms of life the foraminifera are well represented. The genera include *Amphistegina*, *Archædiscus*, *Climacammina*, *Endothyra*, *Lagena*, *Saccammina*, *Fusulina*, *Trochammina*, and *Valvulina*. Some of these genera exhibit a wide geographical range; *Saccammina*, for example, forms

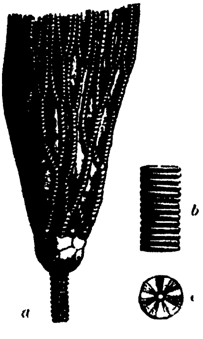

Fig. 354.—Carboniferous Crinoid.

Cyathocrinus planus, Miller. a, calyx, arms and upper part of stem; b, portions of the stem; c, one of the column-joints showing central canal.

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[1] The glacial origin of the phenomena in question has been ably advocated by Mr. W. T. Blanford, 'Manual of Geology of India,' Address to Geological Section of British Association, Montreal; and H. F. Blanford, *Quart. Journ. Geol. Soc.* xxxi. (1875) p. 519. Sutherland, *op. cit.* xxvi. p. 514; W. Waagen, *Jahrb. Geol. Reichsanst.* xxxvii. (1887) p. 143. A. Julien has advocated the glacial origin of the coarse Carboniferous breccias of Central France. *Compt. rend.* cxvii. (1893) p. 255.

beds of limestone in Britain and Belgium, and *Fusulina* plays a still more important part in the Carboniferous Limestone of the region from Russia to China and Japan, as well as in North America; one species of *Valvulina* (*V. palæotrochus*) extends from Ireland to Russia on the one side and to North America on the other. As already noticed, species of organisms, with a wide geographical extension, have also a long geological range, and this is more specially exemplified in such lowly grades of existence as the foraminifera. *Trochammina incerta*, for instance, is found through the whole Carboniferous Limestone series of England, reappears in the Magnesian Limestone of the Permian system, and occurs not only in Britain but in Germany and Russia.[1] The corals (Fig. 353) are represented by tabulate (*Favosites*, *Michelinia*, *Alveolites*, *Chætetes*), and still more by rugose forms (*Amplexus*, *Zaphrentis*, *Cyathophyllum*, *Aulophyllum*, *Clisiophyllum*, *Lithostrotion*, *Lonsdaleia*, *Phillipsastræa*). The Echinoderms were more abundant and varied in this than in any other geological period. Thus among the

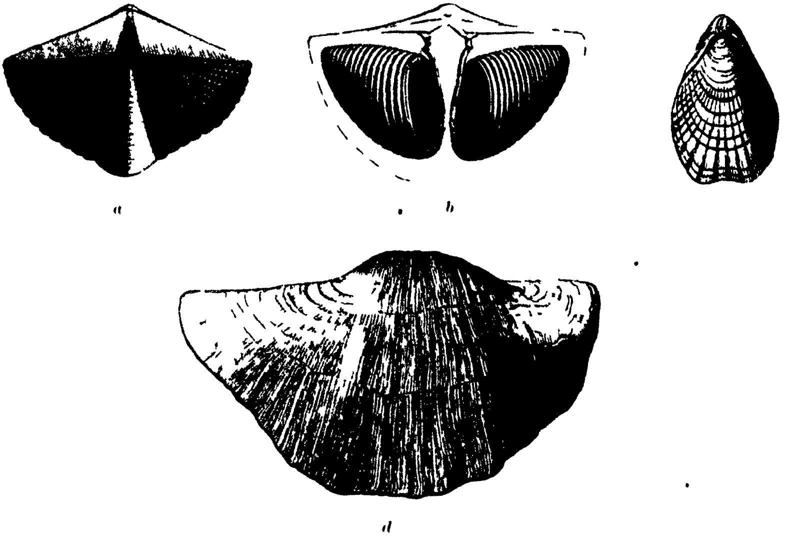

Fig 355.—Carboniferous Brachiopods

a Spirifer hystericus, Schloth *b*, Do interior of dorsal valve, showing spiral calcareous supports for the arms; *c*, Terebratula hastata, Sow ; *d*, Productus giganteus, Martin.

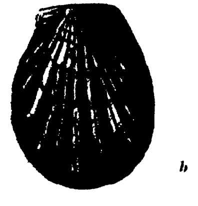

Fig. 356.
Carboniferous Lamellibranchs
a, Conocardium aliforme, Sow ; *b*, Aviculopecten sublobatus, Phill., showing colour-bands.

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[1] H. B. Brady, 'Monograph of Carboniferous and Permian Foraminifera,' *Palæontog. Soc.* (1876).

urchins of the Carboniferous seas were species of *Archæocidaris*, *Palæchinus*, and *Melonites*. The blastoids or pentremites, which now took the place in Carboniferous waters that in Silurian times had been filled by the cystideans, attained their maximum development. But it was the order of crinoids that chiefly swarmed in the seas where the Carboniferous Limestone was laid down, their separated joints now mainly composing solid masses of rock several hundred feet in thickness. Among their most conspicuous genera were *Platycrinus*, *Actinocrinus*, *Cyathocrinus* (Fig. 354), *Poteriocrinus*, and *Rhodocrinus*. Tubicolar annelides abounded, some of the species being solitary and attached to shells, corals, &c., others occurring in small clusters and some in gregarious masses forming beds of limestone. The chief genera are *Spirorbis*, *Serpulites*, *Ortonia*, *Vermilia*. Polyzoa abound in some portions of the Carboniferous Limestone, which were almost entirely composed of them, the genera *Fenestella*, *Ceriopora*, *Rhombopora*, *Sulcoretepora*, *Vincularia*, *Polypora*, and *Glauconome* being frequent. Of the brachiopods (Fig. 355) some of the most common forms are *Productus* (the most characteristic genus), *Spirifer*, *Rhynchonella*, *Athyris*, *Chonetes*, *Orthis*, *Terebratula*, *Lingula*, and *Discina*.[1] Among these are species that appear to range over the whole world, such as *Productus semireticulatus*, *costatus*, *longispinus*, *pustulosus*, *cora*, *aculeatus*, *undatus*; *Streptorhynchus crenistria*; *Spirifer lineatus*, *glaber*; *Athyris globularis*; and *Terebratula hastata*. The higher mollusks now begin to preponderate over the brachiopods. The lamellibranchs (Fig. 356) include forms of *Aviculopecten*, *Posidonomya*, *Leda*, *Nucula*, *Sanguinolites*, *Leptodomus*, *Schizodus*, *Edmondia*, *Anthracosia*, *Modiola*, and *Conocardium*. The gasteropods (Fig. 357) are represented by numerous genera, among which *Euomphalus*, *Natica*, *Pleurotomaria*, *Macrocheilus*, and *Loxonema* are frequent. The genus *Bellerophon* is represented by many species, among which *B. Urei* and *B. decussatus* are frequent. The most abundant

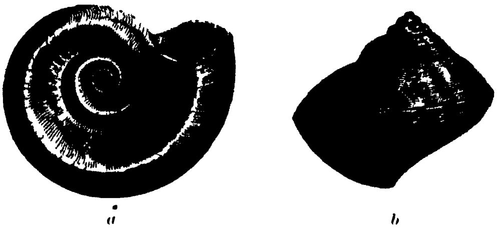

Fig. 357.—Carboniferous Gasteropods.
a, Euomphalus pentangulatus, Sow.; b, Pleurotomaria carinata, Sow., showing colour-bands.

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[1] *Productus* is almost wholly Carboniferous, and in the species *P. giganteus* of the Carboniferous Limestone reached the maximum size attained by the brachiopods, some individuals measuring eight inches across. Other genera had already existed a long time; some even of the species were of ancient date—*Orthis resupinata* of the Carboniferous Limestone and the Devonian *O. striatula* and *Strophomena depressa* had survived, according to Gosselet, from the time of the Bala beds of the Lower Silurian period. (Gosselet, *Esquisse*, p. 118.)

pteropod genus is *Conularia* (Fig. 358), which often attains a length of several inches. Of the cephalopods (Fig. 359), the most abundant and widely distributed are forms of *Orthoceras*, *Cyrtoceras*, *Nautilus*, *Discites*, and *Goniatites*.

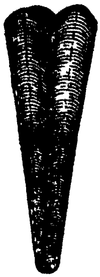

Fig. 358. Carboniferous Pteropod. Conularia quadrisulcata, Sow.

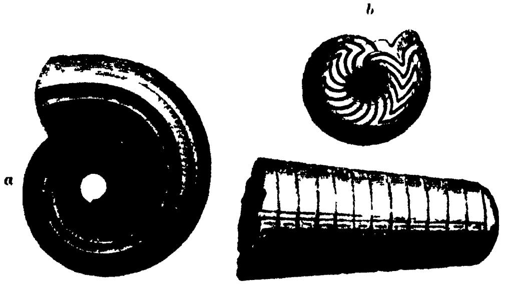

Fig. 359 – Carboniferous Cephalopods
a, Nautilus (Discites) Koninckii, D Orb. , b, Goniatites crenistria, Phill , c, Orthoceras (Breynii, Mart.; laterale, Phill.)

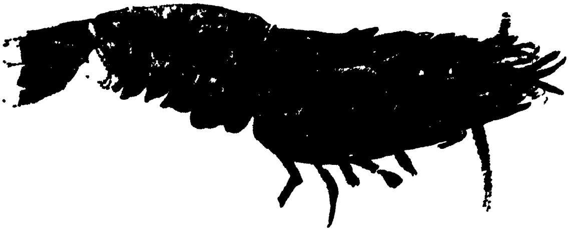

Fig. 360.—Carboniferous Macrourous Crustacean Anthrapalæmon Etheridgii, Peach, twice nat. size

The crustacea present a facies very distinct from that of the previous Palæozoic formations. Trilobites now almost wholly disappear, only four genera of small forms (*Proetus*, *Griffithides*, *Phillipsia*, *Brachymetopus*) being left. But other crustacea are abundant, especially ostracods (*Bairdia*, *Cypridellina*, *Cythere*, *Kirkbya*, *Leperditia*, *Beyrichia*), which crowd many of the shales and sometimes even form seams of limestone. Some schizopod forms are met with (*Palæocaris*) and a few macrura occur not infrequently, particularly *Anthrapalæmon* (Fig. 360) and *Palæocrangon* (*Crangopsis*), also several phyllopods (*Dithyrocaris*, *Ceratiocaris*, *Estheria*, *Leaia*), with the larger merostomatous *Eurypterus* and king-crabs (*Prestwichia*, *Belinurus*). The Carboniferous Limestone of the British Isles has supplied somewhere about 100 genera of fishes, chiefly represented by teeth and spines (*Psammodus*, *Cochliodus*, *Cladodus*, *Petalodus*, *Ctenodus*, *Rhizodus*, *Ctenoptychius*, &c.) Some of these were no doubt selachians which lived solely in the sea, but many, if not all, of the ganoids probably migrated between salt and fresh water; at least their remains are found in Scotland not only in marine limestones, but also in strata full of land-plants, cyprids, and other indications of estuarine or fluviatile conditions. Some of the fishes met with in the plant-bearing type of the Carboniferous system are mentioned on p. 820, together with the air-breathers and other terrestrial organisms.

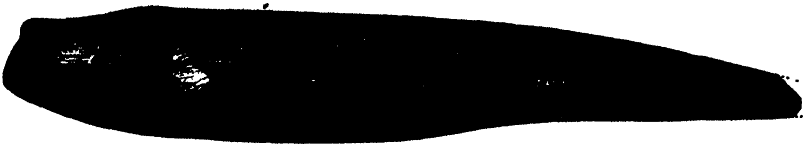

Fig. 361.—Carboniferous Ichthyodorulite, or Dorsal Fish-spine.
Sphenacanthus (Ctenacanthus) hybodoides, Egerton.

It is deserving of remark that in the marine type of the Carboniferous system considerable differences may be observed between the fossils of the limestones and the shales even in the same quarry. The limestones, for example, may be crowded with the joints of crinoids, corals of various kinds, producti and other brachiopods, while the shales above them may contain few of these organisms, but afford polyzoa, *Conularia*, horny brachiopods (*Lingula*, *Discina*), many lamellibranchs, especially pectens, aviculopectens, nuculas, ledas, and gasteropods (*Pleurotomaria*, *Loxonema*, *Bellerophon*, &c.) It is evident that while some organisms flourished only in clear water, such as that in which the

Fig. 362.—Carboniferous Fish.
Jaw of Rhizodus Hibberti, Ag. sp., one-third nat. size.

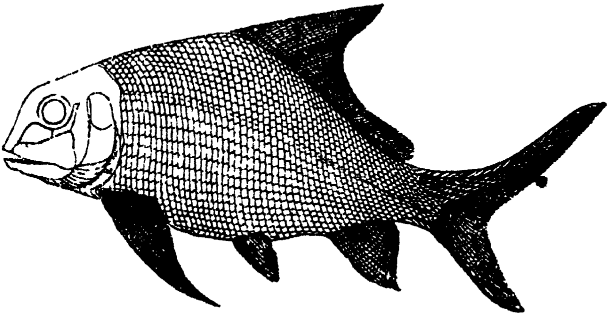

Fig. 363.—Carboniferous Fish.
Eurynotus crenatus, Ag., "Cement-stones" of Scotland (after Traquair).

limestones accumulated, others abounded on a muddy bottom, although some seem to have lived in either situation, if we may judge from finding their remains indifferently in the calcareous and the muddy deposits.

The second phase of sedimentation, that of the coal-swamps, is marked by a very characteristic suite of organic remains. Most abundant of these are the plants, which possess a special interest, inasmuch as they form the oldest terrestrial flora that has been abundantly preserved.[1] This flora is marked by a singular monotony of character all over the world, from the Equator into the Arctic Circle, the same genera, and sometimes even the same species, appearing to have ranged over the whole surface of the globe. It consisted almost entirely of vascular cryptogams, and pre-eminently of Equisetaceæ, Lycopodiaceæ, and Ferns. Though referable to existing groups, the plants presented many remarkable differences from their living representatives. In particular, save in the case of the ferns, they much exceeded in size any forms of the present vegetable world to which they can be assimilated. Our modern horse-tails had their allies in huge trees among the Carboniferous jungles, and the familiar club-moss of our hills, now a low creeping plant, was represented by tall-stemmed *Lepidodendra* that rose fifty feet or more into the air. The ferns, however, present no such contrast to forms still living. On the contrary, they often recall modern genera, which they resemble not merely in general aspect, but even in their circinnate vernation and fructification. With the exception of a few tree-ferns, they seem to have been all low-growing plants, and perhaps were to some extent epiphytic

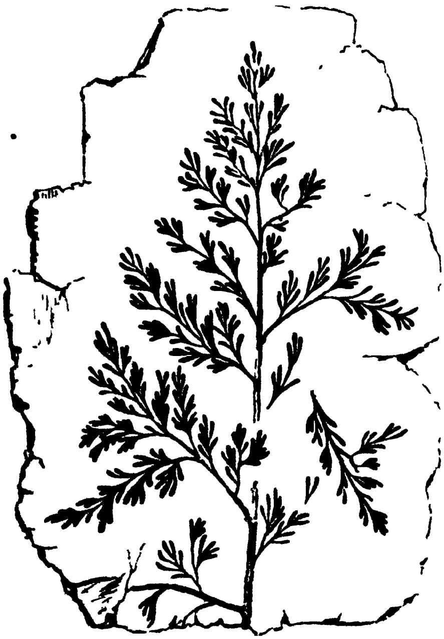

Fig. 364.—Carboniferous Fern. Sphenopteris affinis, Lindl. and Hutt.

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[1] On the Carboniferous flora, consult A. Brongniart, 'Prodrome d'une Histoire des Végétaux fossiles,' 1828; Lindley and Hutton, 'Fossil Flora of Great Britain,' 1831-37. C. E. Weiss, 'Fossile Flora d. jüngsten Steinkohl im Saar-Rhein-Geb,' Bonn, 1869-72. 'Die Flora d. Steinkohlen Formation,' Berlin, 1881. Williamson's Memoirs 'On the Organisation of the Plants of the Coal Measures,' *Phil. Trans.* clxii. (1872), and subsequent volumes. Zeiller, on the Carboniferous flora of Valenciennes, Autun, and Brive, in the series of volumes entitled 'Études des Gites Minéraux de la France,' published by the Ministry of Public Works; Zeiller and Renault on Fossil Flora of Commentry, *Bull. Soc. Indust. Min. St. Etienne*, 2 vols. with Atlas, 1888-90. R. Kidston, *Trans. R. S. Edin.* xxxv. *et seq.*

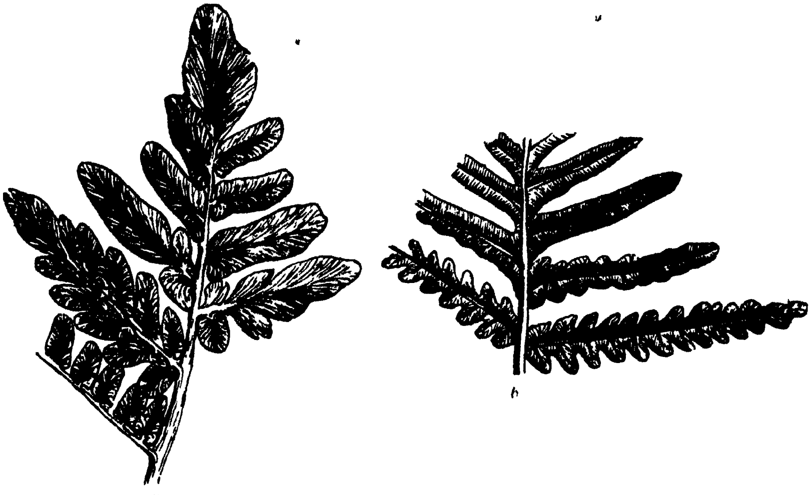

Fig. 365.—Carboniferous Ferns
a, Neuropteris Loshii, Brongn ; b, Alethopteris Gibsoni, Lesq.

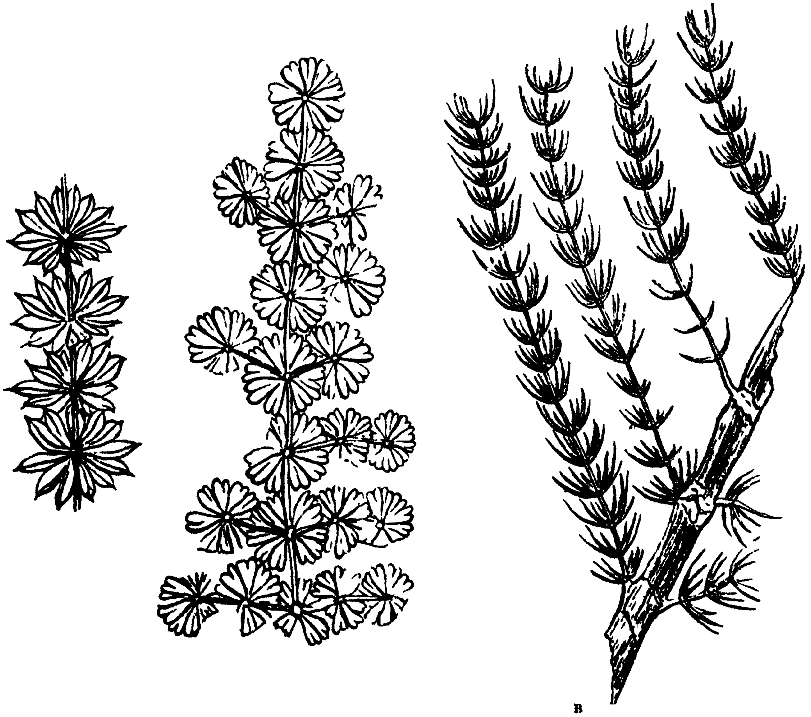

Fig. 366.—A, Annularia sphenophylloides ; B, Asterophyllites.

upon the larger vegetation of the lagoons. Some of the more common genera are *Sphenopteris*, *Neuropteris*, *Cyclopteris*, *Odontopteris*, *Pecopteris*, *Alethopteris*.[1]

Among the Equisetaceæ,[2] the genus *Calamites* is specially abundant. It usually occurs in fragments of jointed and finely-ribbed stems. From the rounded or blunted base of the stem, other stems budded, and numerous rootlets proceeded, whereby the plants were anchored in the mud or sand of the lagoons, where they grew in dense thickets. According to Sir J. Dawson they seem to have fringed the great jungles of Sigillariæ, and to have acted as a filter that cleared the water of its sediment and prevented the vegetable accumulations of the coal-swamps from admixture with muddy sediment. To the foliage of Calamites different generic appellations have been attached (Fig. 366). The name *Asterophyllites* (*Calamocladus*) is given to jointed and fluted stems with verticils of slim branches proceeding from the joints and bearing whorls of long, narrow, pointed leaves. In *Sphenophyllum* the leaves were fewer in number and wedge-shaped; in *Annularia*, the close-set leaves were united at the base. *Calamodendron* is believed by some botanists to be the cast of the pith of a woody stem belonging to some unknown tree, by others it is regarded as only a condition of the preservation of *Calamites*. Some fruits, supposed to belong to the calamaries, have been met with. *Pothocites* has been referred to *Asterocalamites*, *Stachannularia* seems attached to *Annularia*, while others known as *Calamostachys* and *Macrostachys*, are probably the fructification of calamites.

The Lycopods (Fig. 367) were represented by numerous species of the genus *Lepidodendron*, distinguished by the quincuncial leaf-scars on its dichotomous stem. Its branches, closely covered with pointed leaves, bore at their ends cones or spikes (*Lepidostrobus*) consisting of a central axis, round which were placed imbricated scales, each carrying a sporecase. Other conspicuous genera were *Ulodendron*, *Knorria*, *Lepidophloios*, *Halonia*, *Cyclocladia*.

Among the most remarkable trees of the Carboniferous forests were the Sigillarioids, which are believed to have been akin to the Lepidodendra. The genus *Sigillaria* was distinguished by the great height (50 feet or more) of its trunk, which sometimes measured five feet in diameter. Its stem was fluted (Fig. 368), and marked by parallel perpendicular lines of leaf-scars, but as it grew these external markings were lost. The base of the stem passes into the roots known as *Stigmaria*, the pitted and tuberculed stems of which are such common fossils (Figs. 368 B, 369). There can be little doubt, however, that *Stigmaria* was a form of root common to more than one kind of tree. The genus *Cordaites* belonged to a type of tree which by some botanists has been placed among the cycads, by others among the conifers. It attained a great profusion in the time of the Coal-measures. Shooting up to a height of 20 or 30 feet, it carried narrow or broad, parallel-veined leaves, somewhat like those of a Yucca, which were attached by broad bases at somewhat wide distances

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[1] For an essay on the morphology and classification of the Carboniferous ferns see D. Stur, *Sitzb. Akad. Wien.* lxxxvi. (1883).

[2] On Carboniferous Calamaries, consult Weiss, *Abh. Geol. Specialkarte Preussen*, v.

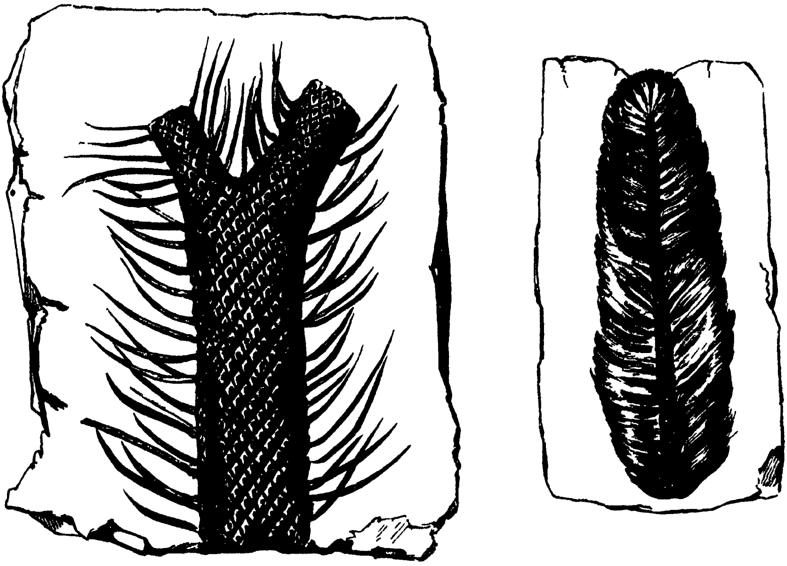

Fig. 367.—Carboniferous Lycopods.
a, Lepidodendron (¼); *b*, Lepidostrobus, nat size.

to the stem, and on their fall left prominent leaf-scars. It bore catkins

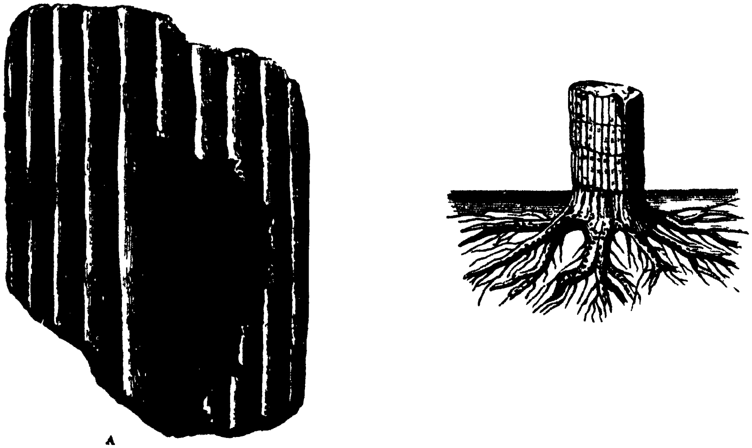

Fig. 368.—A, Sigillaria; portion of decorticated stem; B, Sigillaria stem terminating in Stigmaria Roots and rootlets.

(*Antholithus*) which ripened into berries not unlike those of Yews (*Cardiocarpus*) (Fig. 371). Both of these forms of fructification occur in great abundance in some bands of shale. True Coniferæ were probably abundant on the drier ground, for their stems (*Dadoxylon*, *Araucarioxylon*, *Pinites*) have been met with, particularly in the tuffs of ancient volcanic cones, on which they no doubt grew, and in sandstone, where they occur as drift-wood, perhaps from higher ground (Fig. 370). It should be remembered that the flora preserved in the Carboniferous rocks is essentially that of the low grounds and swamps. The fruit known as *Trigonocarpus* is supposed to be coniferous, somewhat like the fruit of the

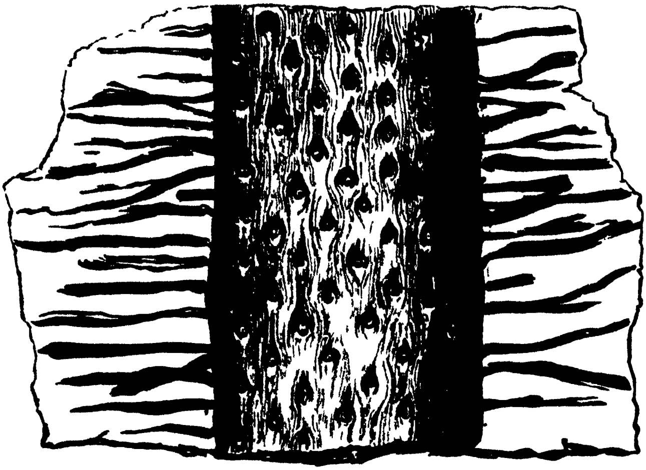

Fig 369.—Stigmaria with attached rootlets.

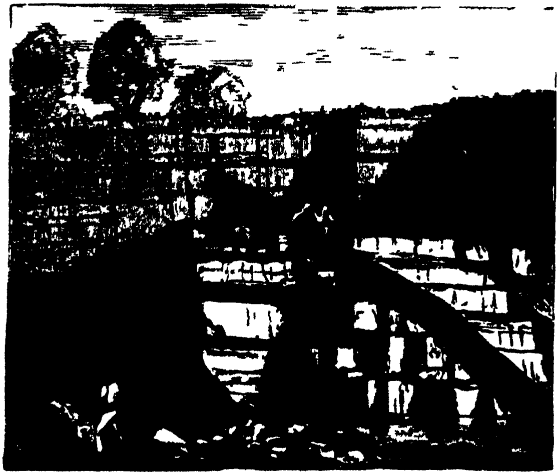

Fig. 370.—Coniferous Tree-trunk imbedded in Sandstone, Craigleith, Edinburgh (after Witham).

living *Salisburia*. That true monocotyledons existed in the Carboniferous period was until recently supposed to be proved by the discovery of a number of spikes, referred to the living order of Aroideæ (*Pothocites*), in the lower part of the Carboniferous system of Scotland; but Mr. R. Kidston has shown that the specimens are almost certainly the fructification of *Bornia*, a genus of Calamite.[1]

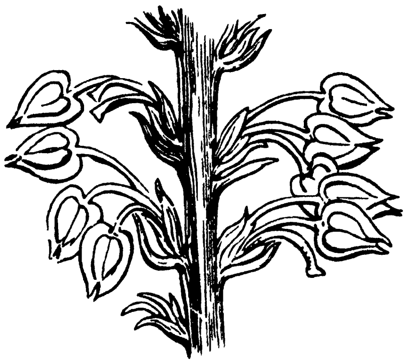
Fig 371.—Antholite with Cardiocarpus.

The animal remains in the coal-bearing part of the Carboniferous rocks are comparatively few. As already stated, in certain bands of shale, coal, and ironstone in the lower half of the Coal-measures, undoubted proofs of the presence of the sea are afforded by the occurrence of some of the familiar shells of the Carboniferous Limestone. But towards the upper part of the Coal-measures, where these marine forms almost entirely disappear (among their last representatives being species of *Lingula* and *Discina*), other mollusks, that were probably denizens of brackish if not of fresh water, occur in abundance. Among the more frequent are *Anthracomya*, *Anthracosia*, and *Anthracoptera*. Crustaceans are chiefly represented by *Beyrichia* and *Estheria*, but large eurypterid forms likewise occur. Fishes are found frequently, remains of the larger kinds usually appearing in scales, teeth, fin-spines, or bones, while the smaller ganoids are often preserved

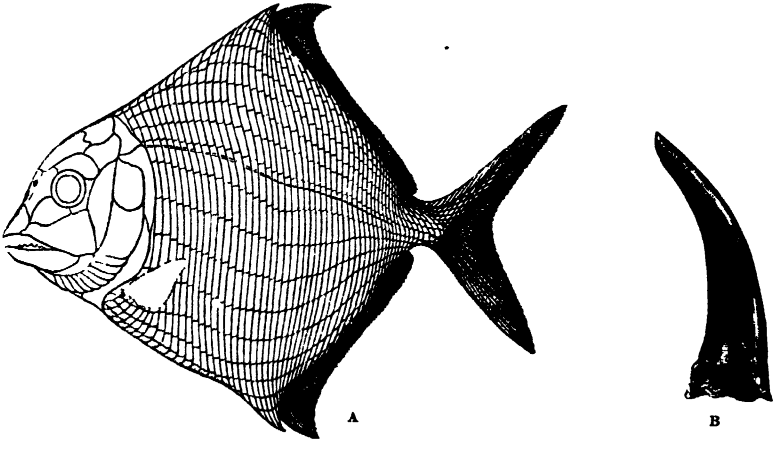

Fig. 372.—Coal-measure Fishes.
A, Cheirodus granulosus, Young, after Traquair; B, tooth of Strepsodus sauroides, Binney, sp.

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[1] *Ann. Mag. Nat. Hist.* May 1883, p. 297.

entire. Common genera are *Ctenodus*, *Strepsodus*, *Cheirodus* (Fig. 372), *Mesolepis*, *Ctenacanthus*, *Gyracanthus*, *Pleuracanthus*, *Ctenoptychius*, and *Megalichthys*.

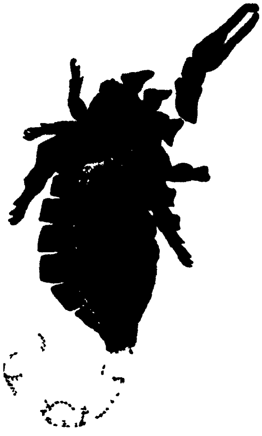
Fig 373.—Carboniferous Scorpion Eoscorpius glaber (B. N. Peach), Lower Carboniferous Eskdale, Scotland

The presence of true air-breathers among the jungles of the Carboniferous period has been established by the discovery of numerous specimens of arachnids, insects, myriapods, and labyrinthodonts. According to the latest census of Mr. Scudder there were known up to 1890 no fewer than 75 species of Carboniferous arachnids.[2] Scorpions (*Eoscorpius*) have been found both in Europe and America, and recently have been obtained in great numbers, in excellent preservation and of gigantic size, in the Lower Carboniferous rocks of Scotland (Fig. 373). Other arachnids occur, including ancient forms of spider (*Protolycosa*). Myriapods, of which upwards of 40 species have been determined, were represented by various plant-eating millipedes (*Xylobius*, *Archiulus*, *Iulus*, *Euphoberia*). True insects likewise flitted through these dense jungles, and during the last ten years the number of species detected has been so large that no fewer than 239 species of orthoptera, 109 of neuroptera, 17 of hemiptera, and 11 of coleoptera have been obtained. Though their remains have been but scantily preserved, we know that they included ancient forms of mayfly, cockroach, cricket, and beetle. It is remarkable that from some coal fields hardly a single trace of insect life has been obtained, while in others great numbers of specimens have been brought to light. A remarkable variety of forms has been found in the Saarbruck Coal-field; but perhaps the greatest number of individual specimens has come from that of Commentry, which up to the end of the year 1884 is computed to have furnished not less than 1300 individuals. Some of the insects were of considerable size. Thus the neuropterous *Archæoptilus* from the Derbyshire Coal-field had a spread of wing of perhaps fourteen inches or more; and a species of *Dictyoneura* (*D. Monyi*) had a wing about twelve inches in length. Others were remarkable for the vividness of their colouring (*Brodia*), the markings of which are still recognisable in the fossil specimens. One of the most singular features yet observed among these ancient insects is the union in the same individual of types of structure which are now entirely distinct. M. Ch. Brongniart has recently shown that wings which were admittedly neuropterous, and were referred to the genus *Dictyoneura*, were really attached to bodies which are unquestionably orthopterous.[2]

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[1] *Bull. U.S. Geol. Surv.* No. 71, 1891.

[2] Ch. Brongniart, *Bull. Soc. Géol. France* (3), xi. p. 142; also Scudder, *Geol. Mag.* 1881, p. 293; *Mem. Boston. Soc. Nat. Hist.* iii. (1883) p. 213; *Proc. Amer. Acad.* 1884,

The Labyrinthodonts which appeared in Carboniferous times as the magnates of the vertebrate world had a salamander-like body with relatively weak limbs and a long tail. Sometimes the limbs seem to have been undeveloped, so that the body was serpent-like. The head was protected by bony plates, and there was likewise a ventral armour of integumentary scales. The British Carboniferous rocks have yielded about 20 genera (*Anthracosaurus*, *Loxomma*, *Ophiderpeton*, *Pholiderpeton*, *Pteroplax*, *Urocordylus*, &c.) These were probably fluviatile animals of predaceous habits, living on fish, crustacea, and other organisms of the fresh or salt waters of the coal-lagoons. The larger forms are believed to have measured 7 or 8 feet in length; some of the smaller examples, though adult and perfect, do not exceed as many inches.[1] The coal-field of Bohemia, which may be in part Permian, has likewise furnished a considerable number of genera and species of Labyrinthodonts and fishes.[2] The terrestrial fauna obtained from the interior of fossil trees in the Coal-measures of Nova Scotia includes land-shells of which several genera are now known (*Dendropupa*,[3] *Pupa*, *Anthracopupa*, *Zonites*, and *Dawsonella*).

Fossil plants do not serve so well for purposes of geological classification as fossil animals (pp. 652, 660, 668). In the Saxon Coal-field, however, Geinitz (1856) distinguished five zones, each characterised by its own facies of vegetation. 1st. The Culm with *Lepidodendron veltheimianum*, *Calamites transitionis*, followed by the remaining four zones, which comprise the productive coal-measures; viz. 2nd, the zone of Sigillarias; 3rd, the zone of Calamites; 4th, the zone of Annularia; and 5th, the zone of Ferns.[4] More recently Grand' Eury has subdivided the Carboniferous system of central France into the following members, according to the succession of vegetation:[5]—

Supra-Carboniferous Flora, simpler and less rich than that below, showing a passage into the Permian flora above, characterised by a rapid diminution of *Alethopteris*, *Odontopteris xenopteroides*, *Dictyopteris*, *Annularia*, *Sphenophyllum*. The Calamites are represented by abundant individuals of *C. varians* and *C. Suckowii*, also *Asterophyllites equisetiformis*; the ferns by *Pecopteris cyatheoides*, *P. hemitelioides*, *Odontopteris minor*, *O. Schlotheimii*, several species of *Neuropteris*, &c.; the Sigillarias by *S. Brardii*, *S. spinulosa*, and *Stigmaria ficoides*; *Cordaites* by numerous narrow-leaved forms; the Calamodendra by a prodigious abundance of some species, *e.g. Calamodendron bistriatum*, *Calamites cruciatus*, *Arthropitus subcommunis*; the conifers by *Walchia piniformis* and some others.

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p. 167; *Bull. U.S. Geol. Surv.* Nos. 31 and 71. H. Woodward, *Q. J. Geol. Soc.* 1872, p. 60. The student interested in the study of fossil insects will find Mr. Scudder's Bibliography of the subject, *Bull. U.S. Geol. Surv.* No. 71 (1890), a valuable book of reference.

[1] Miall, *Brit. Assoc.* 1873, 1874.

[2] C. Feistmantel, *Archiv. Naturw. Landesdurchforsch. Böhmen.* v. No. 3 (1883), p. 55; A. Fritsch, 'Fauna der Gaskohle Bohmens,' 1879 and subsequent years.

[3] J. W. Dawson, *Phil. Trans.* vol. 173 (1882), p. 621.

[4] 'Geognost. Darst. Steink. Sachsen,' 1856, p. 83; 'Die Steinkohlen Deutschlands,' 1865, i. p. 29.

[5] 'Flore Carbonifère du Département de la Loire et du Centre de la France,' Cyrille Grand' Eury, *Mem. Sav. Etrangers*, xxiv. (1877).

Upper Coal Flora (properly so called).—Calamites often abundant—*C. interruptus*, *C. Suckowii*, *C. cannæformis*, *Asterophyllites hippuroides*, *Macrostachya infundibuliformis* (very common), *Annularia brevifolia*, and *A. longifolia* (common throughout), *Sphenophyllum oblongifolium.* Ferns richly developed, particularly of the genera *Pecopteris* (*P. unita*, *arguta*, *polymorpha*, and especially *Schlotheimii*); *Odontopteris* (*O. reichiana*, *Brardii*, *mixoneura*, *xenopteroides*, the last extremely abundant); *Caulopteris macrodiscus*, *Alethopteris Grandini* in great profusion, *Callipteridium* (*C. ovatum*, *gigas*, *densifolia*, common). Lepidodendra have almost disappeared; Sigillariæ are not uncommon (*S. rhitydolepis*, *S. Brardii*), with *Stigmariopsis* and *Syringodendron.* *Cordaites* occurs in great abundance; the conifers are represented by *Walchia piniformis* and a few other species. Calamodendra occur in great abundance, especially *Calamites cruciatus.*

Upper Coal Flora—(Lower Zone, *Flore du terrain houiller sous-supérieure*).—Calamites and Asterophyllites abundant in individuals and species (*C. Suckowii*, *Cistii*, *cannæformis*, *varians*, *approximatus*, *A. rigidus*, *grandis*, *hippuroides*), *Annularia radiata*, *Sphenophyllum.* Among the ferns there are few true sphenopterids, but *Neuropteris* is common (*N. flexuosa*, *auriculata*), also *Odontopteris* (*O. reichiana*, *Schlotheimii*), *Pecopteris* (*P. arborescens*, *pulchra*, *candolliana*, *villosa*, *oreopteridia*, *crenulata*, *aspidoides*, *elegans*), *Caulopteris*, *Psaronius.* Lepidodendra are few (*L. Sternbergii*, *elegans*, *Lepidostrobus sub-variabilis*, *Lepidophloios laricinus*, *Knorria Selloni*, *Lepidophyllum majus*). Sigillarioid forms are likewise on the wane when compared with their profusion below (*Sigillaria elliptica*, *Candollii*, *tessellata*, *elegans*, *grasiana*, *Brardii*, *spinulosa*: *Syringodendron cyclostigma*, *distans*; *Stigmaria ficoides* abundant). Cordaites, however, now becomes the dominant group of plants, but with a somewhat different facies from that which it presents in the middle Coal-measures (*C. borassifolius*, *C. principalis*, *Dadoxylon Brandlingii*, *Cardiocarpus emarginatus*, *Gutbieri*, *major*, *ovatus*). *Calamites cruciatus* makes its appearance, also *Walchia piniformis.*

Middle Coal Flora—(Upper Zone, *Supra-moyenne*).—Calamites numerous (*C. Suckowii*, *Cistii*, *cannæformis*, *ramosus*; *Asterophyllites foliosus*, *longifolius*, *grandis*, *rigidus*; *Annularia minuta*, *brevifolia*; *Sphenophyllum saxifragæfolium*, *Schlotheimii*, *truncatum*, *majus.* Ferns represented by *Sphenopteris* (*S. latifolia*, *irregularis*, *trifoliolata*, *cristata*, &c.) *Prepecopteris* (maximum of this genus), *Pecopteris* (*P. abbreviata*, *villosa*, *Cistii*, *oreopteridia*, &c.), *Caulopteris*, *Neuropteris*, and other genera. Lepidodendra are not infrequent (*Lepidodendron aculeatum*, *Sternbergii*, *elegans*, *rimosum*; *Lepidostrobus variabilis*; *Lepidophloios laricinus*, *Lepidophyllum majus*), and various *Lycopodites.* The proportion of *Sigillaria* is always large (*S. Cortei*, *intermedia*, *Sillimanni*, *tessellata*, *cyclostigma*, *alternans*, *Brongniarti*, *Stigmaria ficoides*, *minor*). *Pseudosigillaria* is abundant, especially *P. monostigma.* *Cordaites* appears in some places abundantly (*C. borassifolius*, *Artisia transversa*, *Cladiscus schnorrianus*), and its fruits are numerous and varied (*Cardiocarpus emarginatus*, *orbicularis*, *ovatus*).

Middle Coal Flora (properly so called), characterised above all by the dominant place of the Sigillarioids, which now surpass the lepidodendroids and form the main mass of the coal-seams. The genus *Sigillaria* here attains its maximum development (*S. Groeseri*, *angusta*, *scutellata*, *intermedia*, *elongata*, *notata*, *alternans*, *rugosa*, *reniformis*, *leopoldina*, and many more; *Pseudosigillaria striata*, *rimosa*, *monostigma*; *Stigmaria ficoides*, *minor*). Lepidodendroids are large and frequent (*Lepidodendron aculeatum*, *obovatum*, *caudatum*, *rimosum*, *Sternbergii*, *elegans*; *Lepidophloios laricinus*; *Ulodendron majus*, *minus*; *Halonia tuberculata*, *tortuosa*, *regularis*; *Lepidophyllum majus*; *Lepidostrobus variabilis*). The ferns are abundant and varied; the Sphenopterids include many species, of which *Sphenopteris Hoeninghausii* and *tenella* are common (also *S. Bronni*, *Schlotheimii*, *tenuifolia*, *rigida*, *furcata*, *elegans*); *Alethopteris* is very plentiful (*A. lonchitica*, *Serlii*, *Mantelli*, *heterophylla*); also *Lonchopteris Bricii* and *L. Röhlii*; *Prepecopteris*, *Pecopteris*, *Megaphyton*, *Neuropteris* (*N. flexuosa*, *Loshii*, *tenuifolia*, *gigantea*), *Cyclopteris*, *Aulacopteris*. The calamites are widely diffused and abundant, especially *Calamites dubius*, *undulatus*, *ramosus*, *decoratus*, *Steinhaueri* ; *Asterophyllites subhippuroides*, *grandis*, *longifolius* ; *Volkmannia binneyana* ; *Sphenophyllum* seems here to reach its maximum, characteristic species being *S. emarginatum*, *saxifragæfolium*, *erosum*, *dentatum*, *truncatum*, *Schlotheimii*. Some coals and shales abound with *Cardiocarpus*, also *Trigonocarpus*, and *Nöggerathia*.

Middle Coal Flora—(Lower Zone, *Flore houillère sous-moyenne*).—Lepidodendroids are characteristically abundant and varied (*Lepidodendron aculeatum*, *obovatum*, *crenatum*, *Haidingeri*, *undulatum*, *longifolium* ; and *Lepidophloios laricinus*, *intermedius*, *crassicaulis* ; *Ulodendron*, abundant in England, *U. dichotomum*, *punctatum*, *majus*, *minus*, &c. ; *Halonia tortuosa*, *regularis*, &c.) Sigillarioids are numerous (*Sigillaria oculata*, *elegans*, *scutellata*, *elongata*, *mamillaris*, *alveolaris*, *reniformis* ; *Stigmaria ficoides*, *minor*, *stellata*, *reticulata* ; *Dictyoxylon*, *Lyginodendron*). Calamites abound (*Calamites cannæformis*, *Suckowii*, *Cistii*, *decoratus*, *approximatus* ; *Asterophyllites subhippuroides*, *longifolius* ; *Volkmannia polystachya*). Ferns likewise form a notable part of the flora, especially sphenopterids (*Sphenopteris latifolia*, *acutifolia*, *elegans*, *dissecta*, *furcata*, *Gravenhorstii*, *nervosa*, *muricata*, *obtusiloba*, *trifoliata*) ; also *Prepecopteris silesiaca*, *oxyphylla*, *Glockeri*, *dentata* ; *Megaphyton majus* ; *Pecopteris ophiodermatica* and other similar forms. The neuropterids become abundant (*Neuropteris heterophylla*, *Loshii*, *gigantea*, *tenuifolia* ; *Cyclopteris obliqua* ; *Alethopteris lonchitica*, &c.) The abundant *Cordaites* of the higher measures are absent, though the fruit *Carpolithes* occasionally occurs.

Infra Coal-measure Flora—(Millstone grit, *l'étage infra-houiller*), characterised essentially by lepidodendroids and stigmarias.—*Lepidodendron aculeatum*, *obovatum*, *crenatum*, *brevifolium*, *caudatum*, *carinatum*, *rimosum*, *volkmannianum* ; *Ulodendron punctatum*, *ellipticum*, *majus* ; *Halonia tuberculosa* ; *Lepidophloios intermedius*, *laricinus*. *Sigillaria* is not very common, but *S. oculata*, *alveolata* (Stern.), *Knorrii*, *trigona*, *minima*, and other species occur. The ferns are more varied than in older parts of the system, sphenopterids being the dominant types (*Sphenopteris distans*, *elegans*, *tridactylites*, *furcata*, *dissecta*, *rigida*, *divaricata*, *linearis*, *acutiloba*, &c.) The genus *Pecopteris* is represented by a few species. *Neuropteris* is comparatively rare (*N. Loshii*, *tenuifolia*), *Alethopteris* appears in the widespread species *A. lonchitica*, and a few others. Calamites are not relatively abundant (*Calamites undulatus*, *Steinhaueri*, *communis*, *cannæformis*, *Cistii* ; *Asterophyllites foliosus*, &c.)

Flora of the Upper Greywacke.—Lepidodendroids are the prevalent forms (*Lepidodendron carinatum*, *polyphyllum*, *volkmannianum*, *rugosum*, *caudatum*, *aculeatum*, *obovatum* ; *Halonia tetrasticha*, *regularis* ; *Ulodendron ovale*, *commutatum*). *Stigmaria* in several species occurs, sometimes abundantly ; but *Sigillaria* is rare (*S. undulata*, *Voltzii*, *costata*, *subelegans*, *venosa*, *Gueranger*i, *verneuillana*). Calamites are not infrequent (*C. Roemeri*, *Voltzii*, *cannæformis*, &c.) The ferns are chiefly sphenopterids (*Sphenopteris dissecta*, *elegans*, *Gersdorfii*, *distans*, *tridactylites*, *schistorum* ; *Cyclopteris tenuifolia*, *Haidingeri*, *flabellata* ; *Prepecopteris aspera*, *subdentata* ; *Neuropteris heterophylla*, *Loshii*).

Flora of the Culm, characterised by the abundance of lepidodendroids of the type of *L. veltheimianum* (with *Knorria imbricata*), by the number of *Bornia transitionis*, associated with *Calamites Roemeri*, *Stigmaria ficoides* (and other species), and by the abundance of the palæopterid ferns (*Palæopteris Machaneti*, *antiqua*, *dissecta*, (*Sphenopteris*) *affinis* (Fig. 364) ; *Cardiopteris frondosa* ; *Rhodea divaricata*, *elegans*, *moravica* ; *Sphenopteris Göpperti*, *Schimperi*, &c.)

Carboniferous Limestone Flora.—The palæopterid ferns reach a maximum (*Palæopteris inæquilatera*, *lindsecæformis*, *polymorpha*, *frondosa*). Sphenopterid forms are found in *Sphenopteris bifida*, *lanceolata*, *confertifolia*. The old genus *Cyclostigma* here disappears (*C. minuta*, *Nathorstii*). The more characteristic lepidodendroids are *Lepidodendron weikianum, veltheimianum, squamosum; Knorria imbricata, acicularis.* The flora includes also *Stigmaria ficoides, rugosa; Bornia transitionis; Asterophyllites elegans,* &c.

§ 2. Local Development.

The European development of the Carboniferous system presents certain well-marked local types, which bring clearly before the mind some of the successive geographical features of the time. During the earlier half of the Carboniferous period, there still lay much land towards the north and north-west of the present European area, whence a continuous supply of sandy and muddy sediment was derived. A sea of moderate depth and clear water extended from the Atlantic across the site of central Ireland, the heart of England, and Belgium into Westphalia. The southern margin of this ancient Mediterranean was probably formed by the ridge of older Palæozoic and crystalline rocks, which, extending from the west of England into the Boulonnais, and from Brittany into central France, sweeps eastward by the uplands of the Ardennes, Hundsrück, Taunus, and Thuringer Wald into Saxony and Silesia. In the deeper and clearer water, massive beds of limestone accumulated; but towards the land, at least on the north side of the sea, there was an increasingly abundant deposit of sand and mud, with occasional seams of coal and sheets of limestone. The whole region underwent slow subsidence and infilling of sediment, until at last vast marshes and jungles occupied tracts that had been previously sea. By degrees, the lower parts of the surrounding land were likewise submerged beneath the accumulating coal-growths, which consequently spread over the sinking areas. Hence, while across the central portions of the Carboniferous region the normal succession of strata presents a lower marine division, consisting mainly of limestone, and an upper brackish-water division, composed of sandstones, shales, and coal-seams, the marginal tracts show hardly any limestone, some of them indeed, as in central France, containing only the highest part of the upper division.

The British Isles.[1]—The general sequence just referred to is well illustrated in the structure of the Carboniferous tracts of Britain, which, being sufficiently extensive to contain more than one type of the system, cast interesting light on the varied geographical conditions under which the rocks were accumulated. As the land, whence the chief supplies of sediment were derived, rose mainly to the north and north-west, while the centre of England and Ireland lay under clear water of moderate depth, the sea shallowed northwards into Scotland, and its bottom was covered with constantly accumulating banks of sand and sheets of mud. Hence vertical sections of the Carboniferous system of Britain differ greatly according to the districts in which they are taken. The subjoined table may be regarded as expressing the typical subdivisions which can be recognised, with modifications, in all parts of the country:—

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[1] For detailed information regarding British Carboniferous rocks and fossils the student may consult, among early works, Phillips' 'Geology of Yorkshire,' 1836, and papers by Prestwich (*Geol. Trans.* 2nd ser. v.), Sedgwick (*op. cit.* iv. *Q. J. Geol. Soc.* viii. *Proc. Geol. Soc.* ii.) Of later date are memoirs by Binney (*Q. J. Geol. Soc.* ii. xviii.), Kirkby (*op. cit.* xxxvi.); Davis and Lees, 'West Yorkshire,' 1878; G. H. Morton, numerous papers in *Proc. Liverpool Geol. Soc.* Hull's 'Coal-Fields of Great Britain,' 4th ed. 1881. The *Memoirs of the Geological Survey* will be found to supply much detailed information for the various Carboniferous tracts of Britain; see, for example, the "Geology of the Yorkshire Coal-Field," by Messrs. Green and Russell, "Geology of Flint and Mold," by A. Strahan. Some local papers are referred to in subsequent notes.

3. Coal-measures	Red and grey sandstones, clays, and sometimes breccias, with occasional seams and streaks of coal and Spirorbis limestone (*Cythere inflata*, *Spirorbis pusillus* (*carbonarius*). Middle or chief coal-bearing series of sandstones, clays, and shales, with numerous workable coals (*Anthracosia*, *Anthracomya*, *Beyrichia*, *Estheria*, *Spirorbis*, &c.) Gannister beds, flagstones, shales, and thin coals, with hard siliceous (gannister) pavements (*Orthoceras*, *Goniatites*, *Posidonomya*, *Aviculopecten*, *Lingula*, &c.)
2. Millstone Grit	Grits, flagstones, and shales, with thin seams of coal.
1. Carboniferous Limestone series	Yoredale group of shales and grits, passing down into dark shales and limestones (*Goniatites*, *Aviculopecten*, *Posidonomya*, *Lingula*, *Discina*, &c.) Thick (Scaur or Main) limestone in south and centre of England and Ireland, passing northwards into sandstones, shales, and coals with limestones (abundant corals, polyzoa, brachiopods, lamellibranchs, &c.) Lower Limestone Shale of south and centre of England (marine fossils like those of overlying limestone). The Calciferous Sandstone group of Scotland (marine, estuarine, and terrestrial organisms), probably represents the Scaur Limestone and Lower Limestone Shale, and graduates downward insensibly into the Upper Old Red Sandstone.

1. CARBONIFEROUS LIMESTONE SERIES AND LOCAL EQUIVALENTS.—In the south-west of England, and in South Wales, the Carboniferous system passes down conformably into the Old Red Sandstone. The passage beds consist of yellow, green, and reddish sandstones, green, grey, red, blue, and variegated marls and shales, sometimes full of terrestrial plants. They are well exposed on the Pembrokeshire coasts, marine fossils being there found even among the argillaceous beds at the top of the Red Sandstone series. They occur with a thickness of about 500 feet in the gorge of the Avon near Bristol, but show less than half that depth about the Forest of Dean. At their base there lies a bone-bed containing abundant palatal teeth. Not far above this horizon, plant-bearing strata are found. Hence these rocks bring before us a mingling of terrestrial and marine conditions. In Yorkshire, near Lowther Castle, Brough, and in Ravenstonedale, alternations of red sandstones, shales, and clays, containing *Stigmaria* and other plants, occur in the lower part of the Carboniferous Limestone. Along the eastern edge of the Silurian hills of the Lake district, at the base of the Pennine escarpment and round the Cheviot Hills, a succession of red and grey sandstones, and green and red shales and marls with plants, underlies the base of the Carboniferous Limestone. It is highly probable, however, that these red strata form merely a local base, and occur on many successive horizons ; so that they should be regarded not as marking any particular period, but rather as indicating the recurrence or persistence of certain peculiar littoral conditions of deposit during the subsidence of the land (p. 516). Farther north, in the southern counties of Scotland, the Upper Old Red Sandstone, with its characteristic fishes, graduates upward into reddish and grey sandstones with Carboniferous plants.

In Devon and Cornwall a type of the Carboniferous system is found, which, though it does not occur elsewhere in Britain, has been ascertained to reappear and to have a wide extension in central Europe. It presents a thick series of well-bedded grits, sandstones, shales, often dark grey, and occasional thin limestones, and passes down conformably into upper Devonian strata. Though much contorted and faulted, like the Devonian formations of the same region, this arenaceous and shaly series has yielded a sufficiently large number of recognisable fossils to show its geological position. The plants resemble generally those found in the Calciferous Sandstone series of Scotland. The animal remains include species of *Orthoceras*, *Goniatites*, *Posidonomya* (*P. Becheri*) *Chonetes*, *Spirifer* (*S. Urei*), *Phillipsia*, &c., an assemblage that also points to a position low down in the Carboniferous system. This series of strata is known as the Culm-measures, and the name Culm has been adopted as the designation of this type of Lower Carboniferous rocks abroad. Bands of tuff, diabase, &c., mark contemporaneous volcanic activity during the deposition of the Devonshire Culm.[1]

In the south and south-west of England, and in South Wales, the base of the Carboniferous system consists of certain dark shales known as Lower Limestone Shale, in which a few characteristic fossils of the Carboniferous Limestone occur. These basement beds vary up to rather more than 400 feet in thickness. They are overlain conformably by the thick mass of limestone, which in Britain and Belgium forms a most characteristic member of the Carboniferous system.

The name Carboniferous Limestone (or Mountain Limestone) was given by Conybeare to the thick mass of limestone which in the south-west of England is interposed between the Old Red Sandstone and the Coal-measures. As the geological structure of the country came to be more fully known, the limestone was found to pass laterally into sandy and argillaceous strata. The term Carboniferous Limestone Series is now applied to this division of the system, which attains its greatest thickness in the north, though the limestone there forms a subordinate part of the whole series. Towards the south, on the other hand, the limestone increases in dimensions till it practically constitutes the entire thickness of the series. In the Pennine chain, which forms the axis of the north of England, the Carboniferous Limestone series attains a thickness of nearly 4000 feet, yet this is not its entire depth, for its base is not seen. Of this great thickness the lowest visible 1600 feet consist of limestone. Traced southward the limestone increases in magnitude, till in the Mendip Hills it attains its maximum thickness of about 3000 feet. Followed, on the other hand, towards the north, the calcareous part of the series diminishes to a few thin seams of limestone, the main mass of rock consisting of sandstone and shale with seams of coal and ironstone. The Pennine chain appears to have been the area of maximum depression during the early part of the Carboniferous period in England. The great and rapid variations in thickness of the limestone may indicate inequalities in the downward movement, and perhaps to some extent irregularities in the growth of corals and the accumulation of calcareous débris. The great mass of 3000 feet of limestone in the Mendip Hills dwindles down to less than 400 feet in the Forest of Dean, a distance of only some 30 miles. The thickness rises in Monmouthshire to 1000 feet, but sinks in Glamorganshire to half that amount. Westward in Caldy Island it swells out again to 2300 feet, while still farther west, on the coast of Pembrokeshire, it disappears altogether.[2]

Where typically developed, the Carboniferous Limestone is a massive well-bedded limestone, chiefly light bluish-grey in colour, varying from a compact homogeneous to a distinctly crystalline texture, and rising into ranges of hills, whence its original name "Mountain Limestone." It is sometimes, especially near Bristol, distinctly oolitic, and often contains occasional scattered irregular nodules and nodular beds of dark chert (phtanite).[3] Though it is abundantly fossiliferous, little has yet been done in working out in detail the successive life-zones of this great mass of rock, as has been performed so well for the corresponding limestone series of Belgium. The fossils commonly stand out on weathered surfaces of the rock, but microscopic investigation shows that even those portions of the mass which appear most structureless consist of the crowded remains of marine organisms. The limestone has been derived entirely from the organisms of the sea-floor, either growing up into a solid mass after the manner of coral-reefs, or spreading over the bottom in sheets of crinoid detritus, or coral sand, mixed with the remains of foraminifera, mollusks, &c. Diversities of colour and lithological character occur, whereby the bedding of the thick calcareous mass can be distinctly seen. Here and there, a more markedly crystalline structure has been superinduced; while along lines of principal joints the rock on either side for a breadth of 20 or 30 fathoms is occasionally converted into yellowish or brown dolomite or "dunstone" (see p. 321). In Derbyshire, sheets of contemporaneous lava, locally termed "toadstone," are interpolated in the Carboniferous Limestone. Other evidences of contemporaneous volcanic action have been noted in the Isle of Man[1] and in Devonshire,[2] but it is in Scotland, as will be immediately referred to, that the most remarkable proofs of abundantly active Carboniferous volcanoes have been preserved.

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[1] De la Beche, 'Geology of Cornwall,' &c. Ussher, *Geol. Mag.* 1887, p. 10, *Proc. Somerset Arch. Nat. Hist. Soc.* xxxviii. (1892) p. 111.

[2] De la Beche (*Mem. Geol. Surv.* i. p. 112) states that the limestone is there overlapped by the Coal-measures. It would be interesting to ascertain if the disappearance of the limestone may not rather be due to an overthrust of the Coal-measures upon it. De la Beche believed that the thickest zone of the limestone lay to the south, from Mendip westward through Caldy Island, and that the thickness rapidly diminished northwards.

[3] The chert bands of the Carboniferous Limestone have been shown by Dr. Hinde to be largely composed of spicules of siliceous sponges, *Geol. Mag.* 1887, p. 435; and 'British Palæozoic Sponges,' *Pal. Soc.* for 1887, p. 98, 1888. Dr. Hinde has also described similar beds from the Permo-Carboniferous rocks of Spitzbergen, *Geol. Mag.* 1888, p. 241.

In the Carboniferous areas of the south-west of England and South Wales, the limits of the Carboniferous Limestone are well defined by the Lower Limestone Shale below, and by the Farewell Rock or Millstone Grit above. In the Pennine area, however, the massive limestone is succeeded by a series of shales, limestones, and sandstones, known as the Yoredale Group. These cover a large area and attain a great thickness. In North Staffordshire they are 2300 feet thick. In Lancashire, they attain still greater dimensions, Mr. Hull having there found them to be no less than 4500 feet thick. Both the lower or main (Scaur) limestone and the Yoredale group pass northwards into sandstones and shales with coal seams. In Northumberland, the Carboniferous Limestone series has been grouped into the following subdivisions:[3]—

Upper Calcareous group, from the base of the Millstone grit to the Great Limestone, 350-1200 feet.
Lower Calcareous group, from the Great Limestone to the bottom of the Dun or Redesdale Limestone, 1300-2500 feet.
Carbonaceous group, Scremerston coals, from the Dun Limestone to the top of the Fell Sandstone, 800-2500 feet.
Fell Sandstone, 500-1600 feet.
Tuedian or Cement Stone group, 500-1500 feet.
Basement conglomerate.

These subdivisions are not all fully developed in any one district, but the average thickness of the whole is at least as great as in districts farther south.

Traced northwards into Scotland, the Carboniferous Limestone series undergoes a still further petrographical and palæontological change. Its massive limestones dwindle down, and are replaced by thick courses of yellow and white sandstone, dark shale, and seams of coal and ironstone, among which only a few thin sheets of limestone are to be met with. Scottish geologists have divided the lower half of their Carboniferous system into two well-marked series—the Calciferous Sandstones and the Carboniferous Limestone. The Calciferous Sandstone series is composed of two groups of strata—the lower of which, or Red Sandstone group, consists of red, white, and yellow sandstones, with blue, grey, green, and red marls or clays, while the upper or Cement-stone group is made up of white and yellow sandstones, blue, grey, green, and black shales and marls, thin coals, seams of limestone and cement-stone, and abundant volcanic rocks. The red sandstones pass down into the Upper Old Red Sandstone, from which they differ in the less intensity of their colour, in the frequent grey and purplish tints they assume, in the absence of the deep brick-red marls so marked in the Upper Old Red Sandstone, and in the occurrence of carbonaceous streaks and tree-trunks, roots, and twigs. In the west of Scotland there occur among the red sandstones (some of which contain Upper Old Red Sandstone fishes) bands of limestone full of true Carboniferous Limestone corals and brachiopods. Hence it is evident that the Carboniferous Limestone fauna had already appeared outside the British area before the final cessation of the peculiar conditions of sedimentation of the Old Red Sandstone period. It was not, however, until these conditions had disappeared that the sea began to invade the lakes and creep over the sinking land of this part of Britain, and to bring with it the abundant Carboniferous Limestone fauna. The Calciferous Sandstones of Scotland represent a phase of sedimentation contemporaneous with the deposition of the Lower Limestone Shale and the Scaur Limestone of the Carboniferous Limestone series of England.

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[1] J. Horne, *Trans. Geol. Soc. Edin.* ii. (1874) p. 332; B. Hobson, *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 432. *Yn Lioar Manninagh*, Douglas, January 1892, p. 337.

[2] De la Beche, 'Report on the Geology of Cornwall,' &c. (1839) p. 119; F. Rutley, 'The Eruptive Rocks of Brent Tor,' *Mem. Geol. Surv.* (1878).

[3] See G. Tate's 'History of Alnwick,' vol. ii. (1869) p. 441; H. Miller, *Brit. Assoc.* (1886) sects. p. 675; and 'Geology of Otterbourne,' &c. *Mem. Geol. Surv.* (1887).

One of the most singular features of the Lower Carboniferous rocks of Scotland is the prodigious abundance of the intercalated volcanic rocks. So varied, indeed, are the characters of these masses, and so manifold and interesting is the light they throw upon volcanic action, that the region may be studied as a typical one for this class of phenomena. (See Book IV. Part VII. Sect. i.) Inland sections are abundant on the sides of the hills and in the stream-courses, while along the sea-shore the rocks have been admirably exposed. Two great phases or types of volcanic action during Carboniferous time may be recognised: (1) Plateaux, where the volcanic materials were discharged so copiously that they now form broad tablelands or ranges of hills, sometimes many hundreds of square miles in extent and 1500 feet or more in thickness; (2) Puys, where the ejections were often confined to the discharge of a small amount of fragmentary materials from a single independent vent, and where, when lavas and more copious showers of ash were thrown out, they generally covered only a small area round the volcano which discharged them.[1]

The Plateau type of eruption was specially developed during the deposition of the Calciferous Sandstones. Its lavas consist of augite-olivine rocks (picrites, limburgites), basalts, porphyrites, and trachytes, while its necks or vents are filled with agglomerates, felsites, and in East Lothian, phonolites.[2] Sheets of tuff are intercalated among the bedded lavas. The Puy type was, on the whole, of later date, reaching its chief development during the time of the Carboniferous Limestone. Its lavas are mostly basalts of various types, together with picrites, diabases, and porphyrites. Tuffs and agglomerates are abundant, not infrequently containing organic remains.

While the scattered vents of the puys, with their associated lavas and tuffs, occur on many horizons, the plateau lavas occupy a tolerably definite position in the Calciferous Sandstones, though sometimes confined to the lower part of that group, sometimes ascending to the very base of the Carboniferous Limestone series. This volcanic zone forms an important feature in the geology of southern Scotland. Composed of nearly horizontal sheets of porphyrite, diabase, and basalt, it extends from the Clyde islands on the west to Stirling on the east, and sweeps in high tablelands through Rewfrewshire and Ayrshire. It reappears in East Lothian, and presents there some interesting and remarkably fresh trachytic lavas. Even far to the south, in Berwickshire, Roxburghshire, and Kirkcudbright, volcanic sheets occupy the same position, and extend across into the English border.

The upper subdivision of the Calciferous Sandstones, known as the Cement-stone group, consists of two sections differing from each other in lithological character, and pointing to distinct conditions of deposit. The lower section is made up of thin-bedded white, yellow, and green sandstones, grey, green, blue, and red clays and shales, with thin bands of pale argillaceous limestone or cement-stone. Seams of gypsum occasionally appear. These strata are, on the whole, singularly barren of organic remains. They seem to have been laid down with great slowness, and without disturbance, in enclosed basins, which were not well fitted for the support of animal life, though fragmentary plants serve to show that the adjoining slopes were covered with vegetation. They underlie the volcanic zone in Stirlingshire and the Lothians, and overlie it in Berwickshire. The upper section is chiefly developed in the basin of the Firth of Forth, where, overlying the volcanic zone, it presents an entirely distinct lithological aspect and is abundantly fossiliferous. It there usually consists of yellow, grey, and white sandstones, with blue and black shales, clay-ironstones, limestones, "cement-stones," and occasional seams of coal. The sandstones form excellent building stones, the city of Edinburgh having been built of them. Some of the shales are so bituminous as to yield, on distillation, from thirty to forty gallons of crude petroleum to the ton of shale; they have consequently been largely worked for the manufacture of mineral-oils. The limestones are usually dull, grey or yellow, and close-grained, in seams seldom more than a few inches thick, and graduate by addition of clay and protoxide of iron into cement-stone; but occasionally they swell out into thick lenticular masses like the well-known limestone of Burdie House, so long noted for its remarkable fossil fishes. This limestone appears to be mainly made of the crowded cases of a small ostracod crustacean (*Leperditia Okeni*, var. *scoto-burdigalensis*). The coal-seams are few and commonly too thin to be workable, though one of them, known as the Houston coal, has been mined to some extent in Linlithgowshire. The fossils of the Cement-stone group indicate an alternation of fresh or brackish water and marine conditions. They include numerous plants, of which the most abundant are *Sphenopteris affinis* (Fig. 364), *Lepidodendron* (two or three species), *Lepidostrobus variabilis* (Fig. 367, *b*), *Araucarioxylon*. Ostracod crustaceans, chiefly the *Leperditia* above mentioned, crowd many of the shales. With these are usually associated abundant traces of the presence of fish, either in the form of coprolites, or of scales, bones, plates, and teeth. The following are characteristic species: *Elonichthys striolatus*, *E. Robisoni*, *Rhadinichthys ornatissimus*, *Nematoptychius Greenockii*, *Eurynotus crenatus* (Fig. 363), *Rhizodus Hibberti*, *Megalichthys* sp., *Gyracanthus tuberculatus*, *Callopristodus* (*Ctenoptychius*) *pectinatus*. At intervals throughout the group, marine horizons occur, usually as shale bands marked by the presence of such distinctively Carboniferous Limestone species as *Spirorbis carbonarius*, *Discina nitida*. *Lingula squamiformis*, *Bellerophon decussatus*, and *Orthoceras cylindraceum*.[1]

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[1] Presidential Address, *Quart. Journ. Geol. Soc.* (1892) p. 105; *Trans. Roy. Soc. Edin.* xxix. p. 437.

[2] F. H. Hatch, *Trans. Roy. Soc. Edin.* (1892) and Presidential Address just cited.

The Cement-stone group of the basin of the Firth of Forth contains a great number and variety of associated volcanic masses of the puy type. At the time when it was deposited, the region of shallow lagoons, islets, and coal-growths was dotted over with innumerable small active volcanic vents. The eruptions continued into the time of the Carboniferous Limestone, but ceased before the deposition of the Millstone Grit.[2]

The Carboniferous Limestone series of Scottish geologists, probably representing the upper part of the Carboniferous Limestone series or Yoredale group of England, consists mainly of sandstones, shales, fire-clays, and coal-seams, with a few comparatively thin seams of encrinal limestone. The thickest of these limestones, known as the Hurlet or Main limestone, is usually about 6 feet in thickness, but in the north of Ayrshire swells out to 100 feet, which is the most massive bed of limestone in any part of the Scottish Carboniferous system. One of a group of limestone beds at the base of the series, it lies upon a seam of coal, and is in some places associated with pyritous shales, which have been largely worked as a source of alum. This superposition of a bed of marine limestone on a seam of coal is of frequent occurrence in Scotland. Above these lower limestones comes a thick mass of strata containing many valuable coal-seams and ironstones (Lower or Edge Coals). Some of these strata are full of terrestrial plants (*Lepidodendron*, *Sigillaria*, *Stigmaria*, *Sphenopteris*, *Alethopteris*); others, particularly the ironstones, and the shales associated with the limestones and ironstones, contain marine shells, such as *Lingula*, *Discina*, *Leda*, *Myalina*, *Euomphalus*. Numerous remains of fishes have been obtained, more especially from some of the ironstones and coals (*Gyracanthus formosus* and other fin-spines, *Megalichthys Hibberti*, *Rhizodus Hibberti*, with species of *Elonichthys*, *Acanthodes*, *Ctenoptychius*, &c.) Remains of labyrinthodonts have also been found in this group of strata, and have been detected even down in the Burdie House limestone. The highest division of the Scottish Carboniferous Limestone series consists of a group of sandstones and shales, with a few coal-seams, and three, sometimes more, bands of marine limestone. Although these limestones are each only about 2 or 3 feet thick, they have a wonderful persistence throughout the coal-fields of central Scotland. As already mentioned (p. 515), they can be traced over an area of at least 1000 square miles, and they probably extended originally over a considerably greater region. The Hurlet limestone, with its underlying coal, can also be followed across a similar extent of country. Hence it is evident that, during certain epochs of the Carboniferous period, a singular uniformity of conditions prevailed over a large region of deposit in the centre of Scotland.

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[1] For descriptions of the Calciferous Sandstone group, see Maclaren, 'Geology of Fife and the Lothians'; also the explanations to accompany the Maps of the Geological Survey of Scotland, particularly those on Sheets 14, 22, 23, 32, 33, and 34. T. Brown, *Trans. Roy. Soc. Edin.* xxii. (1861) p. 385; Kirkby, *Q. Geol. Soc.* xxxvi. p. 559.

[2] For an account of these Puys see Presidential Address, *Quart. Journ. Geol. Soc.* 1892, p. 125; *Trans. Roy. Soc. Edin.* xxix. p. 437. Some of the vents are represented in Figs. 297-301, 303-307 of this text-book.

A distinguishing feature of the Carboniferous Limestone series of Scotland is the abundance of its intercalated volcanic rocks of the puy type. They are well developed in the basin of the Forth and in North Ayrshire. The lavas and tuffs are interbedded among the ordinary sedimentary strata, and the tuffs are sometimes full of plants or of marine shells, crinoids, &c.[1]

The difference between the lithological characters of the Carboniferous Limestone series, in its typical development as a great marine formation, and in its arenaceous and argillaceous prolongation into the north of England and Scotland, has long been a familiar example of the nature and application of the evidence furnished by strata as to former geographical conditions. It shows that the deeper and clearer water of the Carboniferous sea spread over the site of Yorkshire, Derbyshire, and Lancashire; that land lay to the north, and that, while the whole area was undergoing subsidence, the maximum movement took place over the area of deeper water. The sediment derived from the north, during the time of the Carboniferous Limestone, seems to have sunk to the bottom before it could reach the great basin in which foraminifers, corals, crinoids, and mollusks were building up the thick calcareous deposit. Yet the thin limestone bands, which run so persistently among the Lower Carboniferous rocks in Scotland, prove that there were occasional episodes during which sediment ceased to arrive, and when the same species of shells, corals, and crinoids spread northwards towards the land, forming for a time, over the sea-bottom, a continuous sheet of calcareous ooze, like that of the deeper water farther south. These intervals of limestone-growth no doubt point to times of more rapid submergence, perhaps also to other geographical changes, whereby the sediment was for a time prevented from spreading so far. It is further deserving of remark that the fossils in these thin upper limestones in Scotland, though specifically identical with those in the thick lower limestones and in the massive Carboniferous Limestone of central and south-western England, are often dwarfed forms, as if the conditions of life were much less favourable than where the thicker sheets of calcareous material were accumulated. The corals, for instance, are generally few in number and small in size, and the large *Productus* (*P. giganteus*) is reduced to a half or third of the dimensions it attains in its best development.

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[1] See the papers cited already, p. 828.

Viewed as a whole, the Carboniferous Limestone series of the northern part of the British area contains the records of a long-continued but intermittent process of subsidence. The numerous coal-seams, with their under-clays, may be regarded as surfaces of vegetation that grew in luxuriance on wide marine mud-flats. They mark pauses in the subsidence. Perhaps we may infer the relative length of these pauses from the comparative thicknesses of the coal-seams. The overlying and intervening sandstones and shales indicate a renewal of the downward movement, and the gradual infilling of the depressed area with sediment, until the water once more shoaled, and the vegetation from adjacent swamps spread over the muddy flats as before. The occasional limestones serve to mark epochs of more prolonged or more rapid subsidence, when marine life was enabled to flourish over the site of the submerged forests. But that the sea, even though tenanted in these northern parts by a limestone-making fauna, was not so clear and well suited for the development of animal life during some of these submergences as it was farther south, seems to be proved by the paucity and dwarfed forms of the fossils, as well as by the admixture of clay in the stone.

Ireland presents a development of Carboniferous rocks, which on the whole follows tolerably closely that of the sister island. In the northern counties, the lowest members are evidently a prolongation of the type of the Scottish Calciferous Sandstones. In the southern districts, however, a very distinct and peculiar facies of Lower Carboniferous rocks is to be observed. Between the Old Red Sandstone and the Carboniferous Limestone there occurs in the county of Cork an enormous mass (fully 5000 feet) of black and dark-grey shales, impure limestones, and grey and green grits, which have been so affected by slaty cleavage as to have assumed more or less perfectly the structure of true cleaved slates. To these rocks the name of Carboniferous Slate was given by Griffith. They contain numerous Carboniferous Limestone species of brachiopods, echinoderms, &c., as well as traces of land-plants in the grit bands. Great though their thickness is in Cork, they rapidly change their lithological character and diminish in mass, as they are traced away from that district. In the almost incredibly short space of 15 miles, the whole of the 5000 feet of Carboniferous Slate of Bantry Bay seems to have disappeared, and at Kenmare the Old Red Sandstone is followed immediately and conformably by the Limestone with its underlying shale. This rapid change is probably to be explained, as Jukes suggested, by a lateral passage of the slate into limestone; the Carboniferous Slate being, in part at least, the equivalent of the Carboniferous Limestone. Between Bandon and Cork the Carboniferous Slate is conformably overlain by dark shales containing Coal-measure-fossils, and believed to be true Coal-measures. Hence in the south of Ireland, the thick calcareous accumulations of the limestone series appear to be replaced by a corresponding depth of argillaceous sedimentary rocks.[1]

The Carboniferous Limestone swells out to a great thickness, and covers a large part of Ireland. It attains a maximum in the west and south-west, where, according to Mr. Kinahan,[2] it consists in Limerick of the following subdivisions:—

		Feet.
Upper (Burren) Limestone	Bedded limestone	240
	Cherty zone	20
Upper (Calp) Limestone	Limestones and shales	1000
	Cherty zone	40
Lower Limestone	*Fenestella* limestone	1900
	Lower cherty zone	20
	Lower shaly limestones	280
Lower Limestone Shales		100
		3600

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[1] J. B. Jukes, *Memoirs Geol. Survey, Ireland.* Explanation of Sheets 194, 201, and 202, p. 18; Explanation of Sheets 187, 195, and 196, p. 35.

[2] 'Geology of Ireland,' p. 72.

The chert (phtanite) bands which form such marked horizons among these limestones are counterparts of others found abundantly in the Carboniferous Limestone of England and Scotland. Portions of the limestone have a dolomitic character, and sometimes are oolitic. Great sheets of porphyrite, basalt, and tuff, representing volcanic eruptions of contemporaneous date, are interpolated in the Carboniferous Limestone of Limerick.[1] As the limestone is traced northwards, it shows a similar change to that which takes place in the north of England, becoming more and more split up with sandstone, shale, and coal-seams.[2]

2. MILLSTONE GRIT.—This name is given to a group of sandstones and grits, with shales and clays, which runs persistently through the centre of the Carboniferous system from South Wales into the middle of Scotland. In South Wales, it has a depth of 400 to 1000 feet; in the Bristol coal-field, of about 1200 feet. Traced northwards it is found to be intercalated with shales, fire-clays, and thin coals, and, like the lower members of the Carboniferous system, to swell out to enormous dimensions in the Pennine region. In North Staffordshire, according to Mr. Hull, it attains a thickness of 4000 feet, which in Lancashire increases to 5500 feet. These massive accumulations of sediment were deposited on the north side of a barrier of more ancient Palæozoic rocks, which, during all the earlier part of the Carboniferous period, seems to have extended across central England, and which was not submerged until part of the Coal-measures had been laid down. North of the area of maximum deposit, the Millstone Grit thins away to not more than 400 or 500 feet. It continues a comparatively insignificant formation in Scotland, attaining its greatest thickness in Lanarkshire and Stirlingshire, where it is known as the "Moor Rock." In Ayrshire it does not exist, unless its place be represented by a few beds of sandstone at the base of the Coal-measures.

The Millstone Grit is generally barren of fossils. When they occur, they are either plants, like those in the coal-bearing strata above and below, or marine organisms of Carboniferous Limestone species. In Lancashire and South Yorkshire, indeed, it contains a band of fossiliferous calcareous shale undistinguishable from some of those in the Yoredale group and Scaur limestone.

3. COAL-MEASURES.—This division of the Carboniferous system consists of numerous alternations of grey, white, yellow, sometimes reddish, sandstone, dark-grey and black shales, clay-ironstones, fire-clays, and coal-seams. In South Wales it attains a maximum depth of about 12,000 feet; in the Bristol coal-field, about 6000 feet. But in these districts, as in most of the Carboniferous areas of Britain, we cannot be sure that all the Coal-measures originally deposited now remain, for they are generally unconformably covered by later formations. Palæontological considerations, to be immediately adverted to, render it probable that the closing part of the Carboniferous period is not now represented in Britain by fossiliferous strata. Towards the end of the Carboniferous period, possibly also within early Permian time, the Carboniferous strata were in many if not most districts of Britain upheaved so as to be exposed to denudation. In some areas the denudation was so great that the Permian rocks, as in the case of the Magnesian Limestone of Durham, sweep across the denuded edges of the Coal-measures, Millstone grit, and even the higher parts of the Carboniferous Limestone. But these disturbances and erosion were not universal within the British region, for we find that over parts of South Staffordshire these strata are followed with apparent conformability by the Permian sandstones.

In North Staffordshire, the depth of Coal-measures is about 5000 feet, which in South Lancashire increases to 8000. These great masses of strata diminish as we trace them eastwards and northwards. In Derbyshire, they are about 2500 feet thick, in Northumberland and Durham about 2000 feet, and about the same thickness in the Whitehaven coal-field. In Scotland, they attain a maximum of over 2000 feet.

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[1] Presidential Address, *Quart. Journ. Geol. Soc.* 1892, p. 145, and authors there cited.

[2] Hull's 'Physical Geology and Geography of Ireland,' 2nd edit. (1891) p. 49.

The Coal-measures are susceptible of local subdivisions indicative of different and variable conditions of deposit. The following table shows the more important of these :—

GLAMORGANSHIRE.	Feet.	SOUTH LANCASHIRE.	Feet.	CENTRAL SCOTLAND.	Feet.
Upper series : sandstones, shales, &c., with 26 coal-seams, more than . .	3400	Upper series: shales, red sandstones, Spirorbis limestone, ironstone and thin coal-seams .	1600 to 2000	Upper red sandstones and clays, with Spirorbis limestone ; in Fife upwards of .	900
Pennant Grit : hard, thick-bedded sandstones, and 15 coal-seams . .	3246	Middle series: sandstones, shales, clays, and thick coal-seams. The chief repository of coal .	3000 to 4000	True Coal-measures : sandstones, shales, fire - clays, with bands of black-band ironstone, and numerous seams of coal. Thickness in Lanarkshire upwards of . .	2000
Lower series: shales, ironstones, and 34 coal-seams .	450 to 850	Lower or Gannister series : flagstones, shales, and thin coals	1400 to 2000		
Millstone Grit.		Millstone Grit.		Moor Rock, or Millstone Grit.	

The numerous beds of compressed vegetation form the most remarkable feature of the Coal-measures. As already stated, coal-seams in Britain are usually underlain by fire-clay (*mur* of the Belgian coal-fields), which, traversed in all directions by rootlets, and free, or nearly free of alkalies and iron, appears to have been the soil on which the plants that formed the coal grew. A coal-seam accordingly marks there a former surface of terrestrial vegetation, and the shales, fissile micaceous sandstones, and other strata that overlie it show the nature of the sediment under which it was eventually buried.

The Coal-measures of Britain have not yet been very precisely subdivided into palæontological zones. The lower portions or Gannister beds of Lancashire contain at least 70 species of undoubtedly marine fossils, including species of *Goniatites* (*G. Listeri*), *Orthoceras*, *Nautilus*, *Edmondia*, *Posidonia*, *Sanguinolites*, *Aviculopecten* (*A. papyraceus*), *Lingula* (*L. squamiformis*), *Discina*, *Productus*, *Spirifer*, &c Other horizons with marine fossils have been observed in England and Scotland even in the upper Coal-measures.[1] The middle and upper divisions are characterised by the prevalence of species of *Anthracosia*, *Anthracoptera*, and *Anthracomya*. These shells are not met with in association with the more typical marine fauna, but, on the contrary, are mingled with a peculiar assemblage of fishes and reptiles, annelids and crustaceans, such as might be supposed to inhabit brackish or fresh water, together with abundant remains of terrestrial vegetation.[2] Some of the more characteristic fishes are *Strepsodus sauroides* (Fig. 372), *Rhizodopsis sauroides*, *Megalichthys Hibberti*, *Cheirodus granulosus* (Fig. 372), *Janassa linguiformis*, *Sphenacanthus hybodoides* (Fig. 361), *Pleuracanthus lævissimus*, *Ctenoptychius apicalis*. Some species range from bottom to top of the Coal-measures—e.g. *Callopristodus* (*Ctenoptychius*) *pectinatus* and *Gyracanthus formosus*.[3]

Little has yet been done in working out the stratigraphical distribution of the Coal-measure flora of Britain, but some recent progress in this direction has been made by Mr. Kidston, who believes the Coal-measures to be divisible into Upper (Radstock, Somerset), Middle (South Staffordshire, part of Yorkshire), and Lower (part of Yorkshire, Northumberland, Scotland).[4] The late D. Stur, correlating the Coal-measures of this country with those of central Europe mainly by means of the plants, regarded the Coal-measures of Wales and the west of England generally as equivalent to the higher series of Germany, those of central and northern England and Scotland as equivalent to the lower series, both of these series being represented in Lancashire.[1] From plant-remains obtained from the recent boring through the chalk at Dover, Zeiller regards the Coal-measures there as belonging to the upper part of the middle Coal-measures of France.[2]

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[1] J. W. Kirkby, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 747.

[2] Wheelton Hind, *Quart. Journ. Geol. Soc.* xlix. (1893) p. 259.

[3] My friend Dr. Traquair has been kind enough to furnish me with information on this subject, which he has so carefully studied.

[4] *Trans. Roy. Soc. Edin.* xxxv. (1890-91) pp. 63, 391, 419 ; xxxvii. (1893) p. 307.

On the Continent of Europe the Carboniferous system occupies many detached areas or basins—the result partly of original deposition, partly of denudation, and partly of the spread and overlap of more recent formations. There can be no doubt that the English Carboniferous Limestone once extended continuously eastward across the north of France, along the base of the Ardennes, through Belgium, and across the present valley of the Rhine into Westphalia. From the western headlands of Ireland this calcareous formation can thus be traced eastward for a distance of 750 English miles into the heart of Europe. It then begins to pass into a series of shales and sandstones, which, as already remarked, represent proximity to shore, like the similar strata in the north of England and Scotland. In Silesia, and still much farther eastwards, in central and southern Russia, representatives of the Carboniferous Limestone or Culm appear, but interstratified, as in Scotland, with coal-bearing strata. Traces of the same blending of marine and terrestrial conditions are found also in the north of Spain. But over central France, and eastwards through Bohemia and Moravia into the region of the Carpathians, the Coal-measures rest directly upon older Palæozoic groups, most commonly upon gneiss and other crystalline rocks. These tracts had no doubt remained above water during the time of the Carboniferous Limestone, but were gradually depressed during that of the Coal-measures.

France and Belgium.—In Belgium and the north of France the British type of the Carboniferous system is well developed.[3] It comprises the following subdivisions:—

Coal-measures—Système (Étage) Houiller.

Zone of the gas-coals (*Charbons à gaz*, rich bituminous coals, with 28 to 40 per cent of volatile matter), containing 47 seams of coal. *Pecopteris nervosa, P. dentata, P. abbreviata, Alethopteris Serlii, Neuropteris heterophylla, Sphenopteris irregularis, S. macilenta, S. coralloides, S. herbacea, S. furcata, Calamites Suckowii, Annularia radiata, Sphenophyllum erosum, Sigillaria tessellata, S. mamillaris, S. rimosa, S. laticosta, Dorycordaites.*

Zone of the "Charbons gras" (18 to 28 per cent volatile matter), soft caking coal (21 seams), well suited for making coke. *Sphenopteris nummularia, S. macilenta, S. chærophylloides, S. artemisifolia, S. herbacea, S. irregularis, Neuropteris gigantea, Alethopteris Serlii, A. valida, Calamites Suckowii, Sphenophyllum emarginatum, Sigillaria polyploca, S. rimosa, S. laticosta, Trigonocarpus Nöggerathii.*

Zone of the "Charbons demi-gras" (12 to 18 per cent volatile matter), 29 seams of coal, chiefly fitted for smithy and iron-work purposes. *Sphenopteris convexifolia, S. Hœninghausi, S. trichomanoides, S. furcata, S. Schillingsii, S. irregularis, Lonchopteris rugosa, Calamites Suckowii, Annularia radiata, Sigillaria mamillaris, S. elegans, S. piriformis, S. elliptica, S. scutellata, S. Groeseri, S. lævigata, S. rugosa, Halonia tortuosa.*

Zone of the "Charbons maigres." Lean or poor coals (20 to 25 seams), only fit for making bricks or burning lime (9 to 12 per cent volatile matter). *Pecopteris Loshii, P. pennæformis, Neuropteris heterophylla, Alethopteris lonchitica, Sphenophyllum saxifragæfolium, Annularia radiata, Sigillaria conferta, S. Candolli, S. Voltzii, Calamites Suckowii, Lepidodendron rhodeanum, L. pustulatum, Lepidophloios laricinus.*

Zone of *Productus carbonarius. Goniatites diadema, G. atratus, Spirifer mesogonius, S. glaber, S. trigonalis, Streptorhynchus crenistria, Productus semireticulatus, P. marginalis, Avicula papyracea, Schizodus sulcatus.*

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[1] *Jahrb. k. k. Geol. Reichsanst.* 1889.

[2] *Compt. rend.* Oct. 24, 1892. The details of this Dover boring, which has proved the existence of coal-bearing strata beneath the south-east of England, are given by Lorieux, *Ann. Mines*, sér. 9, vol. ii. (1892) p. 227. Bertrand has discussed the relations of this Dover coal-field to those of northern France and Belgium, *op. cit.* iii. (1893) p. 1.

[3] On the Carboniferous rocks of this area see De Koninck, 'Descriptions des Animaux

		Thickness in metres in area of the Sambre.	Thickness in metres in area of the Meuse.
Millstone Grit.	Sandstones or quartzites passing into conglomerates, separated from the Carboniferous Limestone below by carbonaceous shales with some thin coal-seams; chiefly developed towards the north-east (Liège, Aix-la-Chapelle).		
Carboniferous Limestone—Calcaire Carbonifère, Système Calcareux.	Limestone of Visé. Often poor in fossils, distinguished by *Productus giganteus*	50	250
	Limestone of Limont (Napoleon marble of Boulonnais). Fossils numerous: *Productus undatus*, *P. semireticulatus*, *Spirifer glaber*, *S. duplicicostus*, *Rhynchonella pleurodon*, *Terebratula sacculus*	10	
	Limestone of Haut Banc, compact or oolitic in south part of Sambre basin, with *Productus sublævis*; but in north part of that basin, as well as on the Meuse and in the Boulonnais, *Productus cora* replaces *P. sublævis*	40	150
	Dolomite of Namur, well developed between Namur and Liège, and extending into the Boulonnais (Hure dolomite), alternating with grey limestone, containing *Chonetes comoides*	40	
	Limestone of Bachant, grey, bluish-black, or black, with cherts (phtanites). *Productus cora* (and sometimes *P. giganteus*), *Spirifer tricornis*, *Dentalium priscum*, *Euomphalus cirroides*, *Nautilus sulcatus*, *Orthoceras munsterianum*	35	100
	Limestone of Waulsort, grey, often dolomitic; only seen in area of the Meuse. *Spirifer cuspidatus*, *Conocardium aliforme*	0	100
	Limestone of Anseremme, grey and blue-veined limestone and dolomite. *Productus semireticulatus*, *Spirifer mosquensis*, *S. cuspidatus*, *Orthis resupinata*	8	60
	Limestone of Dinant, only found in the Meuse area. *Productus semireticulatus*, *P. Flemingii*, *Pecten intermedius*	0	100
	Limestone of Ecaussines ("petit granite"), crinoidal limestone. *Phillipsia gemmulifera*, *Productus semireticulatus*, *Spirifer mosquensis*, *Streptorhynchus crenistria*, *Orthis Michelini*, *Strophomena rhomboidalis*	25	
	Limestones and shales of Avesnelles, black limestone (16 metres), resting upon argillaceous shales (40 metres). Among the numerous fossils of the limestone are *Productus Flemingii*, *P. Hêberti*, *Chonetes variolaris*, *Rhynchonella pleurodon*, *Spirifer mosquensis*, *Euomphalus æqualis*, *Pecten Sowerbyi*	50	
		258	760 mètres.

The base of these strata passes down conformably into the Devonian system, with which, alike by palæontological and petrographical characters, it is closely linked. The Carboniferous rocks of the north of France and of Belgium have undergone considerable disturbance. A remarkable fault ("la grande faille" of this region) resulting from the rupture of an isoclinal syncline, and the consequent sliding of the inverted

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Fossiles du Terrain Carbonifère de la Belgique' (1842-67). Gosselet's 'Esquisse,' already cited, and his 'L'Ardenne' (1888), chaps. xxii. and xxiii. Mourlon's 'Géologie.' Boulay, 'Terrain Houiller du Nord de la France et ses Vegétaux fossiles,' Lille (1876). Dupont, *Bull. Soc. Roy. Belg.* (1883).

side over higher beds, runs from near Liège westwards into the Boulonnais, with a general but variable hade towards the south. On the southern side lie lower Devonian strata, below which the Carboniferous Limestone, and even Coal-measures are made to plunge. Bores and pits near Liège at the one end, and in the Boulonnais[1] at the other, have reached workable coal, after piercing the inverted Devonian rocks. By continuing the boring the same coals are found at lower levels in their normal positions. Besides this dominant dislocation many minor faults and plications have taken place in the Carboniferous area, some of the coal-seams being folded zig-zag, so that at Mons a bed may be perforated six times in succession by the same vertical shaft, in a depth of 350 yards. At Charleroi a series of strata, which in their original horizontal position occupied a breadth of 8½ miles, have been compressed into rather less than half that space by being plicated into twenty-two zig-zag folds.

Southwards the plateau of crystalline rocks in central France is dotted with more than 300 small Carboniferous basins which contain only portions of the Coal-measures. The most important of these basins are those of the Roannais and Beaujolais, St. Etienne, Autun, Commentry, Gard, and Brive. It would appear, however, that some of the surrounding slates are altered representatives of the lower parts of the Carboniferous system, for Carboniferous Limestone fossils have been found in them between Roanne and Lyons, and near Vichy.[2] Even as far south as Montpellier, beds of limestone full of *Productus giganteus* and other characteristic fossils are covered by a series of workable coals. Grand' Eury, from a consideration of the fossils, regards the coal-basins of the Roannais and lower part of the basin of the Loire, as belonging to the age of the "culm and upper greywacke," or of strata immediately underlying the true Coal-measures. But the numerous isolated coal-basins of the centre and south of France he refers to a much later age. He looks on these as containing the most complete development of the upper coal, properly so-called, enclosing a remarkably rich, and still little-known, flora, which serves to fill up the palæontological gap between the Carboniferous and Permian periods.[3] Some of these small isolated coal-basins are remarkable for the extraordinary thickness of their coal-seams. In the most important of their number, that of St. Etienne, from 15 to 18 beds of coal occur, with a united thickness of 112 feet, in a total depth of 2500 feet of strata. In the basin near Chalons and Autun the main coal averages 40, but occasionally swells out to 130 feet, and the Coal-measures are covered, apparently conformably, by Permian rocks, from which a remarkable series of saurian remains has been obtained. Other Carboniferous areas appear in the north-west of France, where representatives of the Carboniferous Limestone and the coal-bearing series above it are found. The Carboniferous Limestone is also well developed westward in the Cantabrian mountains in the north of Spain, where it likewise is surmounted by coal-bearing strata.[4]

Germany.[5]—The Coal-measures extend in detached basins north-eastwards from

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[1] For the Boulonnais, see Godwin-Austen, *Q. J. Geol. Soc.* ix. p. 231; xii. p. 38; Barrois, *Proc. Geol. Assoc.* vi. No. 1; Report of meeting at Boulogne, *Bull. Soc. Géol. France*, sér. 3, viii. p. 483; Rigaux, *Mém. Soc. Sci. Boulogne*, vol. xiv. (1892); 'Notice Géol. sur le Bas Boulonnais,' Boulogne-sur-mer, 1892.

[2] Murchison, *Q. J. Geol. Soc.* vii. (1851) p. 13; Julien, *Comptes Rendus*, lxxviii. p. 74.

[3] Grand' Eury, 'Flore Carbonifère.' Bertrand, *Bull. Soc. Géol. France*, xvi. (1888) p. 517; Fayol, p. 968 *et seq.*, Memoirs cited *ante*, p. 808; G. Mouret, 'Bassin Houiller de Brive,' 1891.

[4] The coal-field of the Asturias is described by Barrois, 'Recherches sur les Terrains anciens des Asturies,' p. 551. Zeiller (*Mem. Soc. Géol. Nord*, i. 1882) refers the plants to the Middle and Upper Coal-measures of France.

[5] Geinitz, 'Die Steinkohlen Deutschlands,' Munich, 1865; Von Dechen, 'Erläuterungen zur Geol. Karte der Rheinprov.' ii. (1884); C. E. Weiss, 'Fossile Flora der jungsten Steinkohlenformation und des Rothliegenden im Saar-Rhein Gebiete,' 1869-72.

Central France into Germany. One of the most important of these, the basin of Pfalz-Saarbrücken, lying unconformably on Devonian rocks, contains a mass of Coal-measures believed to reach a maximum thickness of not less than 20,000 feet, and divided into two groups:—

2. Upper or Ottweiler beds, from 6500 to 11,700 feet thick, consisting of red sandstones at the top, and of sandstones and shales, containing 20 feet of coal in various seams. *Pecopteris arborescens*, *Odontopteris obtusa*, *Anthracosia*, *Estheria*, *Leaia*; fish-remains.
1. Lower or main coal-bearing (Saarbrucken) beds, 5200 to 9000 feet thick, with 82 workable and 142 unworkable coal-seams, or in all between 350 and 400 feet of coal. Abundant plants of the middle and lower zone of the upper coal flora.

The Franco-Belgian Coal-field is prolonged across the Rhine into Westphalia. The Carboniferous Limestone here dwindles down as a calcareous formation, and assumes the "Culm" phase, passing up into the "flotzleerer Sandstein" or Millstone Grit—a group of sandstones, shales, and pebbly beds some 3000 feet thick, but without coal-seams. These barren measures are succeeded by the true Coal-measures about 10,000 feet thick, with 90 workable seams of coal, having a united thickness of more than 250 feet.

Southern Germany, Bohemia.—Carboniferous rocks occur in many scattered areas across Germany southwards to the Alps and eastwards into Silesia, including representatives both of the lower or Culm phase and of the Coal-measures. The Culm rocks reappear in the Harz, where they are traversed by metalliferous veins and enclose small patches of Coal-measures. The same structure extends into Thuringia, the Fichtelgebirge, Saxony, and Bohemia, the Culm yielding Carboniferous Limestone fossils, as well as *Lepidodendron*, &c., and containing sometimes, as in Saxony, workable coals. This union of fossils characterises the series of shales, sandstones, greywackes, and conglomerates which forms the German Culm. The abundant fauna of the Carboniferous Limestone is reduced to a few mollusks (*Productus antiquus*, *P. latissimus*, *P. semireticulatus*, *Posidonomya Becheri*, *Goniatites sphæricus*, *Orthoceras striatulum*, &c.) The *Posidonomya* particularly characterises certain dark shales known as "Posidonia schists." Of the plants, typical species are *Calamites transitionis*, *Lepidodendron veltheimianum*, *Stigmaria ficoides*, *Sphenopteris distans*, *Cyclopteris tenuifolia*. This flora bears a strong resemblance to that of the Calciferous Sandstones of Scotland. True Coal-measures, however, also occur in these regions, though to a smaller extent than the lower parts of the system. One of the most extensive coal-fields is that of Silesia,[1] where the seams of coal are both numerous and valuable, one of them attaining a thickness of 50 feet. It is noteworthy that in the Coal-measures of eastern and southern Germany horizons of marine fossils occur like those so marked in the corresponding strata of Britain.

The coal-field of Pilsen in Bohemia occupies about 300 square miles. It consists mainly of sandstone, passing sometimes into conglomerate, and interstratified with shales and a few seams of coal which do not exceed a total thickness of 20 feet of coal. In its upper part is an important seam of shaly gas-coal (Plattel, or Brettelkohle), which, besides being valuable for economic purposes, has a high palæontological interest from Dr. Fritsch's discovery in it of a rich fauna of amphibians and fishes. The plants above and below this seam are ordinary typical Coal-measure forms,[2] but these animal remains present such close affinities to Permian types, that the strata containing them may belong to the Permian system (pp. 846, 850). What are believed to be true Permian rocks in the Pilsen district seem to overlie the coals unconformably.

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[1] D. Stur, *Abhandl. k. k. Geol. Reichsanst.* (1877).

[2] From the coal-field of Central Bohemia C. Feistmantel enumerated 278 species of plants, of which 187 were ferns (*Sphenopteris*, *Neuropteris*, *Odontopteris*, *Cyatheites*, *Alethopteris*, *Megaphyton*, &c.) *Archiv. Naturw. Landesdurchforsch. Bohmen*, v. No. 3, 1883. For the amphibian remains, see Fritsch's 'Fauna der Gaskohle.'

Alps, Italy.—The Carboniferous strata of the Alps have been already (p. 622) referred to in connection with the metamorphism of that region. In the western part of the chain they occur embedded in or associated with a great series of reddish sandstones, conglomerates and red-greenish shales or slates, which occasionally become quite crystalline, and cannot indeed be satisfactorily separated from what have been regarded as the primitive schists of the mountains. To these strata the name of "Verrucano" has been given. That they are partly, at least, of Carboniferous age is shown by the characteristic flora, amounting to upwards of 60 species, which the dark carbonaceous bands have yielded.[1]

In Italy the Carboniferous and Permian rocks are so closely related and so similar that it is doubtful to which system some of the intermediate portions should be assigned. At Monte Pizzul in the Carnic Alps, the lower strata contain *Productus giganteus* and *P. semireticulatus*, while the highest are characterised by numerous forms of *Fusulina*, *Fenestella*, &c.[2] In other parts of the same region lower strata of the age of the Culm of Germany have been described by Stur and Stache.

Russia.—Over a vast region of the east of Europe Carboniferous limestones, sandstones, shales, and thin coal-seams are spread out almost horizontally. They unite the marine and terrestrial types of sedimentation so characteristic of the north of Britain. In the central provinces of Russia, the Moscow basin or coal-field of Tula, said to occupy an area of 13,000 square miles, lies conformably on the Old Red Sandstone or Devonian system, and contains limestones full of Carboniferous Limestone fossils, and a few poor seams of coal. In the south of the empire, the coal-field of the Donetz, covering an area of 11,000 square miles, contains 60 seams of coal, of which 44, having a united thickness of 114 feet, are workable. Again, on the flanks of the Ural Mountains, the Carboniferous Limestone series has been upturned and contains some workable coal-seams. It would appear, therefore, that this particular type of mingled marine and terrestrial strata of Carboniferous age, occupies a vast expanse under later formations in the east of Europe. Since so much of the Russian development of the Carboniferous system consists of limestone, it is interesting to find that it contains many of the familiar fossil species of the Carboniferous Limestone of Western Europe. Thus in the Ural region, according to Prof Tschernyschew, the Carboniferous system may be divided into five zones, of which the lowest, a limestone containing *Productus giganteus*, *P. striatus*, *Chonetes papilionacea*, &c., and the next a limestone with *Spirifer mosquensis*, may be regarded as corresponding to the typical Carboniferous Limestone of the west. The three upper zones, viz. those of (*a*) *Syringopora parallela*, *Spirifer striatus*, &c., (*b*) *Productus cora*, and (*c*) *Spirifer fasciger* and *Conocardium uralicum*, are probably equivalent to the Millstone Grit and Coal-measures.[3] One of the most abundant and persistent organisms of the upper zones is the foraminifer *Fusulina*. The upper Carboniferous rocks on the west side of the Urals shade upwards into the base of the Permian system, and show a commingling of Carboniferous and Permian fossils.

Even as far north as **Spitzbergen** a characteristic Carboniferous flora has been obtained, comprising 26 species of plants, half of which are new, but among which we recognise such common forms as *Lepidendron Sternbergii* and *Cordaites borassifolius.*[4]

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[1] For an essay on these rocks, see L. Milch's 'Beiträge zur Kenntniss des Verrucano,' Leipzig, 1892. The metamorphism of Carboniferous and Permian rocks in the Alps of Savoy is described by P. Termier, *Bull. Carte Géol. France*, ii. (1891) p. 367.

[2] A. Tommasi, *Boll. Soc. Geol. Ital.* viii. p. 564 ; C. F. Parona and L. Bozzi, *op. cit.* ix. pp. 56, 71.

[3] *Ann. Soc. Géol. Nord*, xvii. (1890) p. 201. Nikitin, *Mem. Com. Géol. Russ.* v. (1890), No. 5.

[4] Heer, *Flora Fossilis Arctica*, iv. (1877) p. 4.

Africa.—The sea in which the brachiopods, corals, and crinoids of the Carboniferous Limestone lived extended across the Mediterranean basin into Africa. Species of *Productus*, *Athyris*, *Spirifer*, *Streptorhynchus*, *Orthis*, *Cyathophyllum*, &c., have been obtained in the western Sahara between Morocco and Timbuctoo.[1] The red sandstones, which extend into the peninsula of Sinai and thence into Palestine, have yielded stems of *Lepidodendron* and *Sigillaria*, and an intercalated limestone contains *Orthis Michelini* and *Streptorhynchus crenistria*.[2] A number of characteristic brachiopods of the Carboniferous Limestone have also been obtained from the hills in the Egyptian desert to the west of the Gulf of Suez, such as *Rhynchonella pleurodon*, *Productus semireticulatus*, *Spirifer striatus*.[3] In Southern Africa the existence of Carboniferous rocks has long been known. Above certain slates and sandstones (Bokkeveldt) containing fossils with Devonian affinities come the quartzites of Cape Colony, enclosing *Lepidodendron* and other Carboniferous plants. These are unconformably overlain by the "Dwyka Conglomerate," probably in great part of volcanic origin, and the Ecca mudstones and sandstones, some 4000 feet thick. After another great unconformability come the Kimberley shales and the "Karoo Beds," which have been compared with the Permian and Trias rocks of Europe.[4]

Asia.—The Carboniferous system is extensively developed in Asia. In China, where it covers an area of many thousand miles, forming a succession of vast tablelands, it has been found by Richthofen to be composed of three stages: 1st, a massive brown bituminous limestone, which from its foraminifera (*Fusulina*, *Fusulinella*, *Lingulina*, *Endothyra*, *Valvulina*, *Climacammina*) is obviously the equivalent of the Carboniferous Limestone of Europe. It is covered by (2nd) productive Coal-measures with both bituminous and anthracitic coals, and containing a characteristic Coal-measure flora, among which are numerous ferns of the genera *Sphenopteris*, *Palæopteris*, *Cyclopteris*, *Neuropteris*, *Callipteridium*, *Cyatheites*, &c., also species of *Calamites*, *Sphenophyllum*, *Lepidodendron* (including *L. Sternbergii*), *Stigmaria* (*S. ficoides*), *Cordaites*, and others. 3rd, Upper Carboniferous—sandstones, conglomerates and thin limestones, containing marine fossils, among which are the cosmopolitan brachiopods mentioned on p. 811.[5]

Australasia.—In Australia, important tracts of true Carboniferous rocks, with coal-seams, range down the eastern colonies, and are specially developed in New South Wales, where they are divisible into: 1st, Lower Carboniferous—sandstones, conglomerates, limestones, shales, much disturbed in some places, traversed by valuable auriferous quartz-reefs, and yielding abundant plant-remains (*Lepidodendron veltheimianum*, *L. nothum*, species of *Bornia*, *Sphenopteris*, *Calamites*, *Rhacopteris*, &c.) 2nd, Upper or Permo-Carboniferous, including a series of coal-bearing strata, both below and above which are thick masses of calcareous conglomerates and sandstone abounding in marine fossils. The coal-seams are sometimes 30 feet thick, and among the plants associated with them are five species of *Glossopteris*, also species of *Phyllotheca*, *Annularia*, and *Nöggerathiopsis*. The genus *Glossopteris* was formerly believed to be entirely Mesozoic, and its occurrence with true Carboniferous organisms was for a time denied. There can now be no doubt, however, that it appears among strata in which are found the widespread and characteristic Carboniferous Limestone forms *Lithostrotion basaltiforme*, *L. irregulare*, *Fenestella plebeia*, *Athyris Royssii*, *Orthis Michelini*, *O. resupinata*, *Productus aculeatus*, *P. cora*, *P. longispinus*, *P. punctatus*, *P. semireticulatus*, and many more.[6] Prof. T. W. E. David, in summarising our knowledge of the coal-bearing rocks of New South Wales, gives a thickness of 11,150 feet to the Upper or Permo-Carboniferous series, and 11,300 feet to the Lower Carboniferous. The productive Coal-measures lie in the upper series. In descending order these are: the Newcastle group, Tomago or East Maitland group, and Greta group. The Permo-Carboniferous series is separated by an unconformability, and a strong break in the flora, from the lower division, in the top of which sheets of andesitic dolerite with tuffs occur.[1] Among the marine strata of the Lower Coal-measure series R. D. Oldham found coarse conglomerates, which he compared with those of India as probably indicative of glacial transport.[2]

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[1] G. Stache, *Denksch. Acad. Wiss. Wien*, xlvi. (1893).

[2] R. Tate, *Quart. Journ. Geol. Soc.* xxvii. (1871) p. 404.

[3] J. Walther, *Zeitsch. Deutsch. Geol. Ges.* (1890) p. 419.

[4] A. H. Green, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 240.

[5] Richthofen, 'China,' vols. ii. and iv.

[6] See the papers by W. B. Clarke, R. Etheridge jun., De Koninck and Wilkinson cited on p. 776.

In New Zealand the rocks assigned to the Carboniferous system consist, in the upper part, of fine clay-slates, becoming calcareous and passing down into true limestones at the base, from which *Spirifer bisulcatus*, *S. glaber*, *Productus brachythœrus*, &c., have been obtained. They are thus probably Lower Carboniferous; and, though they do not yield coal, they are geologically important from the large share they take in the structure of the great mountain-ranges, and from the occasional abundant development in them of contemporaneous igneous rocks, which are associated with metalliferous deposits.[3]

North America.—Rocks corresponding in geological position and the general aspect of their organic contents with the Carboniferous system of Europe are said to cover an area of more than 200,000 square miles in the United States and British North America. The following table shows the subdivisions which have been established among them:—

Carboniferous.	Coal-measures,—a series of sandstones, shales, ironstones, coals, &c., varying from 100 feet in the interior continental area to 4000 feet in Pennsylvania, and more than 8000 feet in Nova Scotia. The plant remains include forms of *Lepidodendron*, *Sigillaria*, *Stigmaria*, *Calamites*, ferns, and coniferous leaves and fruits. The animal forms embrace in the marine bands species of *Spirifer*, *Productus*, *Bellerophon*, *Nautilus*, &c. Among the shales and carbonaceous beds numerous traces of insect life have been obtained, comprising species related to the may-fly and cockroach. Spiders, scorpions, centipedes, limuloid crabs, and land-snails like the modern *Pupa* have also been met with. The fish remains comprise teeth and ichthyodorulites of selachian genera, and a number of ganoids (*Eurylepis*, *Cœlacanthus*, *Megalichthys*, *Rhizodus*, &c.) Several labyrinthodonts occur, and true reptiles are represented by one saurian genus found in Nova Scotia, the *Eosaurus*. In the Western Territories the Upper Carboniferous rocks consist of a massive group of limestone 2000 feet thick, resting on Lower Carboniferous ("Weber Quartzite" of King), estimated at 6000 to 10,000 feet, but with no coals.
	Millstone Grit,—a group of arenaceous and sometimes conglomeratic strata, with occasional coal-seams, only 25 feet thick in some parts of New York, but swelling out to 1500 feet in Pennsylvania.

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[1] *Trans. Austral. Assoc. Soc.* vol. ii. (1890) pp. 459-465. O. Feistmantel, *Mem. Geol. Surv. N.S. Wales, Palæontology*, No. 3, 1890, p. 37. The Carboniferous and Permo-Carboniferous corals of New South Wales are described by E. Etheridge jun., *op. cit.* No. 5, 1891. For recent information on the Australian Coal-fields, see papers by Walker, Robertson, & Cox, *Trans. Fed. Inst. Min. Eng.* ii. (1891) pp. 268, 321; iv. (1893) p. 83. For a detailed account of the Permo-Carboniferous rocks and fossils of Queensland, see R. L. Jack and E. Etheridge jun., 'The Geology and Palæontology of Queensland,' 1892, chaps. vi.-xxii.

[2] *Rec. Geol. Surv. India*, xix. part i. p. 39.

[3] Hector's 'Handbook of New Zealand,' 1883, p. 35. F. W. Hutton, *Quart. Journ. Geol. Soc.* 1885, p. 200.

Sub-Carboniferous.

In the Mississippi basin, where the sub-Carboniferous groups are best developed, they present the following subdivisions in descending order :—

Chester group.—Limestones, shales, and sandstones, sometimes 600 feet.
St. Louis group.—Limestones with shale, in places 250 feet.
Keokuk group.—Limestone with chert layers and nodules.
Burlington group.—Limestone, in places with chert and hornstone, 25 to 200 feet.
Kinderhook group.—Sandstones, shales, and thin limestones, 100 to 200 feet, resting on the Devonian black shale.

The sub-Carboniferous groups are mainly limestones, but contain here and there remains of the characteristic Carboniferous land vegetation. Crinoids of many forms abound in the limestones. A remarkable polyzoon, *Archimedes*, occurs in some of the bands. The brachiopods are chiefly represented by species of *Spirifer* and *Productus* ; the lamellibranchs by *Myalina*, *Schizodus*, *Aviculopecten*, *Nucula*, *Pinna*, and others ; the cephalopods by *Orthoceras*, *Nautilus*, *Goniatites*, *Gyroceras*, &c. The European genus of trilobite, *Phillipsia*, occurs. Numerous teeth and fin-spines of selachian fishes give a further point of resemblance to the European Carboniferous Limestone. Some of the rippled rain-pitted beds contain amphibian footprints—the earliest American forms yet known. Large deposits of gypsum occur in this stage in Nova Scotia.

The highest members of the Carboniferous system in the United States are usually barren of coal. The characteristic Lepidodendra and Sigillariæ disappear and their place is taken by plants with Permian affinities (Pennsylvania, Ohio, W. Virginia), whilst in Illinois, Texas, and New Mexica, Permian reptiles occur in this part of the system. In these regions no definite upper limit to the system can be found, as it shades upwards into strata which may represent the Permian series of Europe.[1]

Section v. Permian (Dyas).

§ 1. General Characters.

The Carboniferous rocks are overlain, sometimes conformably, but in Europe for the most part unconformably, by a series of red sandstones, conglomerates, breccias, marls, and limestones. These used to be reckoned as the highest part of the Coal formation. In England they received the name of the "*New* Red Sandstone" in contradistinction to the "*Old* Red Sandstone" lying beneath the Carboniferous rocks. The term "Poikilitic" was formerly proposed for them, on account of their characteristic mottled appearance. Eventually they were divided into two systems, the lower being taken as the summit of the Palæozoic series of formations, and the upper as the basement of the Mesozoic. This arrangement, which is mainly based on the difference between the organic remains of the two divisions, is generally adopted by geologists.[2]

Following the usual grouping, we remark that the portion of the red strata classed as Palæozoic has received the name of "Permian," from its wide development in the Russian province of Perm, where it was studied by Murchison, De Verneuil, and Keyserling. In Germany, where it exhibits a well-marked grouping into two great series of deposits, the name "Dyas," proposed by Geinitz, has on that account been to some extent adopted. In North America, where no good line of subdivision can be made at the top of the Carboniferous system, the term "Permo-Carboniferous" has been used to denote the transitional beds at the top of the Palæozoic series, and this name has been proposed for use also in Europe and in Australia.

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[1] See Report to the International Geological Congress, London, 1888, by J. J. Stevenson. Full details of the N. American Carboniferous system are given in Correlation Papers—Devonian and Carboniferous, by H. S. Williams, *Bull. U.S. Geol. Survey*, No. 80 (1891).

[2] Some writers, however, still contend that the red rocks of Europe between the summit of the Carboniferous and base of the Jurassic system form really one great series, the break between them being merely local. See, for example, H. B. Woodward, *Geol. Mag.* 1874, p. 385 ; 'Geology of England and Wales,' 2nd edit. (1887) p. 207, and authorities cited by him.

In Europe two distinct types of the system can be made out. In one of these (Dyas) the rocks consist of two great divisions: (1) a lower series of red sandstones and conglomerates, and (2) an upper group of limestones and dolomites. In the other (Russian or Permian) the strata are of similar character, but are interstratified in such a way as to present no twofold petrographical subdivision.

Rocks.—The prevailing materials of the Permian series in Europe are undoubtedly red sandstones, passing now into conglomerates and now into fine shales or "marls." In their coarsest forms, these detrital deposits consist of conglomerates and breccias, composed of fragments of different crystalline or older Palæozoic rocks (granite, diorite, gneiss, mica-schist, quartzite, greywacke, sandstone, &c.), that vary in size up to blocks a foot or more in diameter. Sometimes, these stones are well rounded, but in many places they are only partially so, while, here and there, they are quite angular, and then constitute breccias. The pebbles are held together by a brick-red ferruginous, siliceous, sandy, or argillaceous cement. The sandstones are likewise characteristically brick-red in colour, generally with green or white layers and spots of decoloration. The "marls," showing still deeper shades of red, and passing occasionally into a kind of livid purple, are crumbling sandy clay-rocks, sometimes merging into more or less fissile shales. Of the argillaceous beds of the system the most remarkable are those of the Marl-slate or Kupferschiefer—a brown or black often distinctly bituminous shale, which in certain parts of Germany is charged with ores of copper. The limestone, so characteristic a feature in the "Dyas" development of the system, is a compact, well-bedded, somewhat earthy, and usually more or less dolomitic rock (Zechstein). It is the chief repository of the Permian invertebrates. With it are associated bands of dolomite, either crystalline and cavernous (Rauchwacke) or finely granular and crumbling (Asche); also bands of gypsum, anhydrite, and rock-salt. In certain localities (the Harz, Bohemia, Autun) seams of coal are intercalated among the rocks, and with these, as in the Coal-measures, are associated bituminous shales and nodular clay-ironstones. In Germany, France, the south-west of England, and the south-west of Scotland, the older part of the Permian system contains abundant contemporaneous masses of eruptive rock, among which occur diabase, melaphyre, porphyrite, and various forms of quartz-porphyry.

Some of the breccias in the west of England contain striated stones, which, according to Sir A. C. Ramsay, indicate the existence of glaciers in Wales during the Permian period.[1]

The Permian system in the greater part of Europe, from the prevalent red colour of its rocks, the association of dolomite, rock-salt, saliferous clays, gypsum, and anhydrite, and the remarkably impoverished and stunted aspect of its fauna, has evidently been deposited in isolated basins in which the water, cut off more or less completely from the sea, underwent concentration until chemical precipitation could take place. Looking back at the history of the Carboniferous rocks, we can understand how such a change in physical geography was brought about. The Carboniferous Limestone sea having been by upheaval excluded from the region, wide lagoons occupied its site, and these, as the land slowly went down, crept over the old ridges that had for so many ages been prominent features. The downward subterranean movement was eventually varied by local elevations, and at last the Permian basins came to be formed. As a result of these disturbances, the Permian rocks overlap the Carboniferous, and even cover them in complete discordance, the denudation of the older formation having been, in some places, enormous before the Permian strata were laid down.[2]

In Southern Europe and thence eastwards, abundant evidence of open seas is supplied by limestone containing a rich fauna of foraminifera, gasteropods, orthoceratites, and early precursors of the ammonites.

LIFE.—The conditions under which the Permian rocks of the greater part of Europe were deposited must have been eminently unfavourable to life. Accordingly we find that these rocks are on the whole singularly barren of organic remains. So great is the contrast between them and older formations, that instead of such rich faunas as those of the Silurian, Devonian, and Carboniferous systems, they have yielded only somewhere about 300 species of organisms.

The flora of the older Permian rocks presents many points of resemblance to the Carboniferous.[3] According to Grand' Eury upwards of 50 species of plants are common to the two floras. Among the forms which rise into the Permian rocks and disappear there, are *Calamites Suckowii*, *C. approximatus*, *Asterophyllites equisetiformis*, *A. rigidus*, *Pecopteris elegans*, *Odontopteris Schlotheimii*, *Sigillaria Brardii* (and others), *Stigmaria ficoides*, *Cordaites borassifolius*, &c. Others, which are mainly Permian, are yet found in the highest coal-beds of France, *e.g.* *Calamites gigas*, *Calamodendron striatum*, *Arthropitus ezonata*, *Tæniopteris abnormis*, *Walchia piniformis*, &c. But the Permian flora has some distinctive characters; such as the variety and quantity of the ferns united under the genus *Callipteris*, which do not occur in the Coal-measures, the profusion of tree-ferns (*Psaronius*, of which 24 species are described by Göppert, *Protopteris*, *Caulopteris*, &c.)

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[1] *Quart. Journ. Geol. Soc.* 1855, p. 185.

[2] In some places, the whole of the Carboniferous system has been worn away down to the Carboniferous Limestone, upon which the Permian sandstones and conglomerates have been directly deposited. The discordance, however, sometimes disappears, and then the Carboniferous and Permian rocks shade into each other.

[3] See Göppert's 'Die Fossile Flora der Permischen Formation,' Cassel, 1864-65.

of *Equisetites*, and of the conifers *Walchia piniformis* and *W. filiciformis*, and the occurrence of species of *Gingko*. The most characteristic plants throughout the German Permian groups are *Odontopteris obtusiloba*, *Callipteris conferta*, *Calamites gigas*, and *Walchia piniformis*. The last representatives of the ancient tribes of the lepidodendra, sigillarioids, and calamites are found in the Permian system. Cycads now make their appearance and increase in importance in the succeeding geological periods. Among their Permian forms are the genera *Pterophyllum* and *Medullosa*. In extra-European Permian areas a commingling of Palæozoic and Mesozoic types of vegetation has been observed, forms of *Voltzia*, *Pterophyllum*, and *Glossopteris* being there prominent.

The impoverished fauna of the Permian rocks of central Europe is found almost wholly in the limestones and brown shales, the red conglomerates and sandstones being, as a rule, devoid of organic contents. A few corals (*Stenopora*, *Polycœlia*) and polyzoa (*Fenestella*, *Polypora*, *Synocladia*, *Acanthocladia*) occur in the limestones, the latter sometimes even in continuous masses like coral-reefs, as in the dolomite-reef of S.E. Thuringia. The echinoderms are few, the chief crinoids being species of *Cyathocrinus*. Among the brachiopods, of which some 30 species are known, the most conspicuous are forms of *Productus*, *Camarophoria*, *Spirifer*, *Strophalosia* (Fig. 374), and *Aulosteges*. Lamellibranchs are more numerous, characteristic genera in the German limestone being *Axinus* (Fig. 374), *Allorisma*, *Solemya*, *Schizodus*, *Edmondia*, *Arca*, *Avicula*, *Bakevellia* (Fig. 374), *Pecten*. Among the few gasteropods, forms of *Chemnitzia*, *Turbo*, *Murchisonia*, *Pleurotomaria*, and *Chiton* have been recorded. An occasional *Nautilus*, *Orthoceras*, or *Cyrtoceras* represents the rich cephalopodan fauna of the Carboniferous Limestone.

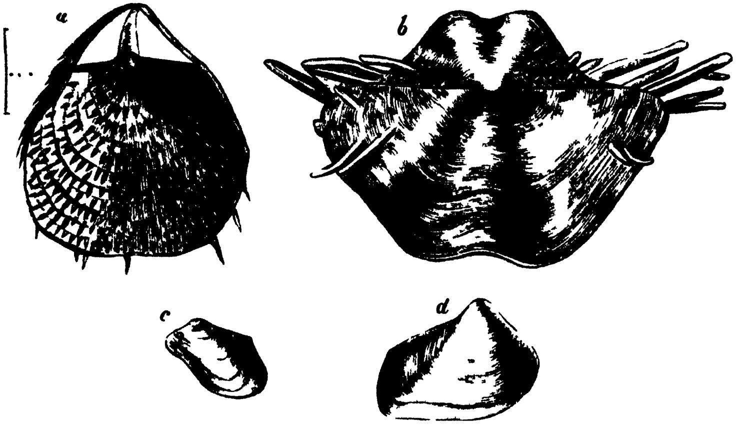

Fig 374.—Permian Mollusks.
a, Strophalosia Goldfussi, Munst. (enlarged); *b*, Productus horridus, Sow.; *c*, Bakevellia tumida, King; *d*, Axinus (Schizodus) Schlotheimii, Geinitz.

It is not, however, from the sites of the brackish inland seas of western and central Europe that we may obtain the best conception of the animal life of Permian time. If we pass southwards into the Alps and the Mediterranean basin, or eastwards into the Uralian region and thence into India, we find that while some of the European forms extend into these areas, they are accompanied by many hundreds of other species.

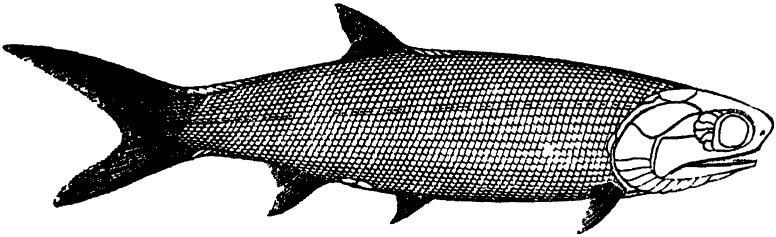

Fig. 375.—Palæoniscus macropomus, Ag. (½), Kupferschiefer. From a restoration by Dr. Traquair.

One of the most remarkable features in this richer and more varied fauna is the great number of the cephalopods and the affinities which many of them present to the Ammonites so characteristic of Mesozoic time. Among the Permian genera of this type are *Adrianites*, *Arcestes*, *Medlicottia*, *Popanoceras*, *Stacheoceras*, *Thalassoceras*, and *Waagenoceras*. They are associated with many forms of *Orthoceras*, *Gyroceras*, and *Nautilus*—a blending of Palæozoic and Mesozoic types which is much less clearly shown in central and western Europe.

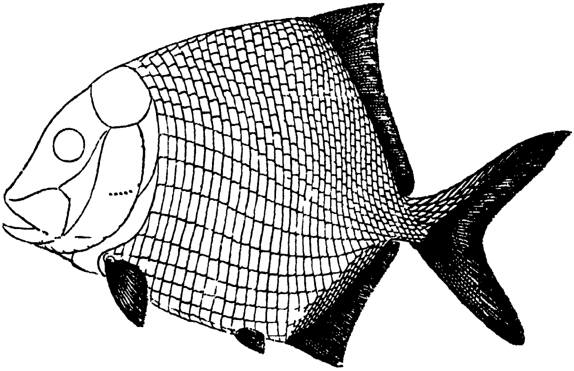

Fig. 376.—Platysomus striatus, Ag. (¼), Magnesian Limestone. Restored by Dr. Traquair.

Fishes, which are proportionately better represented in the Permian rocks than the invertebrates, chiefly occur in the marl-slate or Kupferschiefer, the most common genera being *Palæoniscus* (Fig. 375), which is specially characteristic, *Platysomus* (Fig. 376), *Pygopterus*, *Acanthodes*, *Acrolepis*, and *Amblypterus*.

Amphibian life appears to have been abundant in Permian times, for some of the sandstones of the system are covered with footprints, assigned to the extinct order of Labyrinthodonts. Occasional skulls and other bones have been met with referable to *Archegosaurus*, *Lepidotosaurus*, *Zygosaurus*, &c. The remains of comparatively few forms, however, had been found until the remarkable discoveries of Dr. Anton Fritsch in the basins of Pilsen and Rakowitz in Bohemia. The strata of these localities have been already (p. 837) referred to as containing an abundant and characteristic coal-flora, yet with a fauna that is as decidedly like that of known Permian rocks. According, therefore, as we give preference to the plants or the animals, the strata may be ranked as Carboniferous or as Permian. Of the numerous Saxon and Bohemian species of amphibians, Prof. Credner in Dresden and Dr. Fritsch in Prague have published elaborate descriptions. Among the genera are *Protriton* (*Branchiosaurus*), a form resembling an earth-salamander in possessing gills, and of which the largest specimen is only about 2½ inches long), *Sparodus*, *Hylonomus*, *Dawsonia*, *Melanerpeton*, *Dolichosoma*, *Ophiderpeton*, *Macromerion*, *Urocordylus*, *Limnerpeton*, *Hyloplesion*, *Seeleya*, *Microbrachis*, *Diplospondylus*, *Nyrania*, and *Dendrerpeton*. Some of these forms were remarkably small. The adult Protritonidæ, for instance, were only from 2½ to 6½ inches long. Other types, however, attained a much larger size, *Palæosiren*, for instance, being estimated to have had a length of 45 feet.[1] From the corresponding strata of Autun in Central France, M. Gaudry has also described some interesting forms—*Actinodon*, *Protriton*, *Euchirosaurus*, a larger and more highly organised type than any previously known from the Palæozoic rocks of France, but inferior to another subsequently found at Autun, which he has named *Stereorhachis*, and which was distinguished by completely ossified vertebræ and other proofs of higher organisation that connect it with the Theriodonts of Russia and Southern Africa and with the Pelycosaurians of the United States.[2] Various other anomodont reptiles have been met with, referable to a number of genera (*Naosaurus*, *Clepsydrops*). Of still higher grade were other types to which the names *Proterosaurus* and *Palæohatteria* (Rhynchocephalia) have been given.

§ 2. Local Development.

Britain.[3]—In England on a small scale, a representative is to be found of the two contrasted types of the European Permian system. On the east side of the island, from the coast of Northumberland southwards to the plains of the Trent, a true "Dyas" development is exhibited, the Magnesian Limestone and Marl Slate forming the main feature of the system; on the west side of the Pennine chain, however, the true Permian or Russian facies is presented. The system is in this country most nearly complete in the north-western and south-western counties of England. Arranged in tabular form the rocks of the western and eastern areas may be grouped as follows:—

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[1] A. Fritsch, 'Fauna der Gaskohle und der Kalksteine der Permformation Bohmens,' Prag, 1881. See also H. Credner on *Stegocephali* from the Rothliegende of Dresden, *Z. Deutsch. Geol. Ges.* 1881-86; E. D. Cope, *Amer. Nat.* xviii. (1884).

[2] Gaudry, *Bull. Soc. Géol. France*, vii. (3 sér.) p. 62; ix. p. 17; xiii. p. 44; xiv. pp. 430, 444. 'Les Enchaînements du Monde Animal,' 1883, *Arch. Mus. Nat. Paris*, x. (1887).

[3] Sedgwick, *Trans. Geol. Soc.* (2) iii. (1835) p. 37; iv. 383; De la Beche, 'Geology of Cornwall, Devon,' &c. p. 193; Murchison, 'Siluria,' p. 308; W. King, 'Monograph of the Permian Fossils,' *Palæontog. Soc.* 1850; Hull, 'Triassic and Permian Rocks of Midland Counties of England,' in *Mem. Geol. Surv.* 1869; *Q. J. Geol. Soc.* xxv. 171; xxix. p. 402; xlviii. p. 60; Ramsay, *op. cit.* xxvii. p. 241; Kirkby, *op. cit.* xiii. xvi. xvii. xx.; E. Wilson, *op. cit.* xxxii. p. 533; D. C. Davies, *op. cit.* xxxiii. p. 10; H. B. Woodward, *Geol. Mag.* 1874, p. 385; 'Geology of England and Wales,' p. 210; T. V. Holmes, *Q. J. Geol. Soc.* xxxvii. p. 286; W. T. Aveline, H. H. Howell in various *Memoirs Geol. Surv.*

	W. of England.	E. of England.
Red sandstones, clays, and gypsum	600 ft.	50–100 ft.
Magnesian Limestone Marl Slate	10–30 ,,	600 ,,
Lower red and variegated sandstone, reddish brown and purple sandstones and marls, with calcareous conglomerates and breccias	3000 ,,	100–250 ,,

Lower Sandstone.—This subdivision attains its greatest development in the vale of the Eden, where it consists of brick-red sandstones, with some beds of calcareous breccia, locally known as "brockram," derived principally from the waste of the Carboniferous Limestone. These red rocks extend across the Solway into the valleys of the Nith and Annan in the south of Scotland, where they lie unconformably on the Lower Silurian rocks, from which their breccias have generally been derived, though near Dumfries they contain some "brockram." The breccias have evidently accumulated in small lakes or narrow fjords. In the basin of the Nith, and also in Ayrshire, numerous small volcanic vents and sheets of diabase, picrite, olivine-basalt, porphyrite and tuff are associated with the red sandstones, marking a volcanic district of Permian age. The vents rise through Coal-measures as well as more ancient rocks. Similar vents in Fifeshire, also piercing Coal-measures, have been referred to the same volcanic period. In Devonshire similar rocks mark the outpouring of lavas in the early part of the Permian period.[1] But these volcanic phenomena were on a feeble scale. They are interesting as marking the close of the long continuance of volcanic activity during Palæozoic time. Neither in Britain nor throughout most of the Continent has evidence been found of renewed eruptions during the long lapse of the Mesozoic ages.[2]

In central England, Staffordshire, and the districts of the Clent and Abberley Hills, the Permian system contains some remarkable brecciated conglomerates which attain a thickness of 400 feet. They have been shown by Ramsay[3] to consist in large measure of volcanic rocks, grits, slates, and limestones, which can be identified with rocks on the borders of Wales. Some of their blocks are three feet in diameter and show distinct striation. These Permian drift-beds, according to Ramsay, cannot be distinguished by any essential character from modern glacial drifts, and he had no doubt that they were ice-borne, and, consequently, that there was a glacial period during the accumulation of the Lower Permian deposits of the centre of England.

Like red rocks in general, the Lower Permian beds are almost barren of organic remains. Such as occur are indicative chiefly of terrestrial surfaces. Plant remains occasionally appear, such as *Ullmannia* (supposed to be of marine growth), *Lepidodendron dilatatum*, *Calamites*, *Sternbergia*, *Dadoxylon*, and fragments of coniferous wood. The cranium of a labyrinthodont (*Dasyceps*) has been obtained from the Lower Permian rocks at Kenilworth. Footprints, referred to members of the same extinct order, have been observed abundantly on the surfaces of the sandstones of Dumfriesshire, and also in the vale of the Eden.

Magnesian Limestone Group.—This subdivision is the chief repository of fossils in the Permian system of England. Its strata are not red, but consist of a lower zone of hard brown shale with occasional thin limestone bands (Marl Slate) and an upper thick mass of dolomite (Magnesian Limestone). The latter is the chief feature in the Dyas development of the system in the east of England. Corresponding with the Zechstein of Germany, as the Marl Slate does with the Kupferschiefer, it is a very variable rock in lithological characters, being sometimes dull, earthy, fine-grained, and fossiliferous, in other places quite crystalline, and composed of globular, reniform, botryoidal, or irregular concretions of crystalline and frequently internally radiated dolomite. It is divisible in Durham into three sections—1st, Lower compact limestone, about 200 feet thick; 2nd, Middle fossiliferous and brecciform limestone, 150 feet; 3rd, Upper yellow concretionary and botryoidal limestone, 250 feet. The Magnesian Limestone runs as a thick persistent zone down the east of England.[1] In southern Yorkshire it is split up by a central zone of marls and sandstones with gypsum. It is represented on the Lancashire, Cheshire, and Cumberland (Penrith) side by bright red and variegated sandstones covered by a thin group of red marls, with numerous thin courses of limestone, containing *Schizodus*, *Bakevellia*, and other characteristic fossils of the Magnesian Limestone. Murchison and Harkness have classed as Upper Permian certain red sandstones with thin partings of red shale, and an underlying band of red and green marls and gypsum. These rocks, seen at St. Bees, near Whitehaven, resting on a magnesian limestone, have not yet yielded any fossils.

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[1] *Geol. Mag.* (1866) p. 243; *Quart. Journ. Geol. Soc.* (1892), Presid. Address, p. 147, and authorities cited.

[2] *Op. cit.* p. 162.

[3] *Q. J. Geol. Soc.* xi. p. 181.

The Magnesian Limestone group of the north of England has yielded about 150 species belonging to some 70 genera of fossils—a singularly poor fauna when contrasted with that of the Carboniferous system below. The brachiopods include *Productus horridus*, *Camarophoria humbletonensis*, *C. Schlotheimii*, *Strophalosia Goldfussi*, *Lingula Credneri*, and *Terebratula elongata*. Of the lamellibranchs *Axinus* (*Schizodus*) *Schlotheimii*, *Bakevellia tumida*, *B. antiqua*, *B. ceratophaga*, *Mytilus squamosus*, and *Arca striata* are characteristic. The univalves are represented by 10 genera and 26 species, including *Pleurotomaria* and *Turbo* as common genera. Nine genera of fishes have been obtained chiefly in the Marl Slate, of which *Palæoniscus* and *Platysomus* are the chief. These small ganoids are closely related to some which haunted the lagoons of the Carboniferous period. Some reptilian remains have been obtained from the Marl Slate, particularly *Proterosaurus Speneri* and *P. Huxleyi*, while *Lepidotosaurus Duffii* has been found in the Magnesian Limestone.

Fine sections are exposed on the south coast of Devonshire of coarse breccias and red sandstones, which have been assigned by some writers to the Trias, by others to the Permian series. They rest unconformably on Devonian strata, and have been derived from the degradation of these rocks. At many places in the interior to the west of Exeter bands of basic amygdaloidal lavas are intercalated in them, like the volcanic sheets in the Permian sandstones of Scotland. Owing to the apparent passage of these red strata upwards into others which graduate into the base of the Lias, and are undoubtedly Triassic, the whole series of red sediments has not unnaturally been regarded as referable to the Trias. The resemblance of the lower parts of the series to Permian rocks, coupled with the occurrence of volcanic bands in them, has more recently been held to justify the separation of these lower breccias and sandstones from the rest, as representatives of the Permian series of the Midlands.[2]

Germany,[3] &c.—The "Dyas" type of the system attains a great development along the flank of the Harz Mountains, also in the Rhine province,[1] Thuringia, Saxony, Bavaria, and Bohemia. On the south side of the Harz it is grouped into the following subdivisions :—

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[1] In borings at Middlesboro' beds of salt and gypsum have been found at a depth of more than 1300 feet from the surface, and below a mass of limestone 67 feet thick, which is believed to be the Magnesian Limestone.

[2] Hull, *Quart. Journ. Geol. Soc.* xlviii. (1892) p. 60; A. Irving, *op. cit.* xliv. (1888) and xlviii. p. 68.

[3] H. B. Geinitz, 'Die animalischen Ueberreste der Dyas,' 1861-62, Suppl. 1880-82; 'Zur Dyas in Hessen,' *Festsch. Ver. f. Naturk.* Cassel, 1886; Geinitz and Gutbier, 'Die

Zechstein Group.	Upper.	Anhydrite, gypsum, rock-salt, marl, dolomite, fetid shale, and limestone. The amorphous gypsum is the chief member of this group; the limestone is sometimes full of bitumen.
	Middle.	Crystalline granular (*Rauchwacke*) and fine powdery (*Asche*) dolomite (sometimes 150 feet thick, with gypsum at the bottom).
	Lower.	Zechstein-limestone, an argillaceous thin-bedded compact limestone 15 to 30 (sometimes even 90) feet thick. Kupferschiefer—a black bituminous shale not more than about 2 feet thick. Zechstein-conglomerate, and calcareous sandstone.
Rothliegende Group.	Upper.	Red sandstones (*Kreuznach*), red shales (*Monzig*), with sheets of melaphyre and masses of quartz-porphyry conglomerate (*Sotern*).
	Lower.	Sandstones and conglomerates lying on black shales with poor coal-seams (*Lebach*). Sandstones and shales, with some seams of coal resting on red and grey sandstones, with bands of impure limestone (*Cusel*).

The name "Rothliegende," or rather "Rothtodtliegende" (red-layer or red-dead-layer), was given by the miners because their ores disappeared in the red rocks below the copper-bearing Kupferschiefer. The coarse conglomerates have been referred by Ramsay to a glacial origin, like those of the Abberley Hills. They attain the enormous thickness of 6000 feet or more in Bavaria. One of the most interesting features of the formation is the evidence of the contemporaneous outpouring of great sheets of quartz-porphyry, granite-porphyry, porphyrite, and melaphyre, with abundant interstratifications of various tuffs, not unfrequently enclosing organic remains. From the very nature of its component materials, the Rothliegende is comparatively barren of fossils; a few ferns, calamites, and remains of coniferous trees are found in it, particularly in the lower part of the group, where they form thin seams of coal.

The plants, all of terrestrial growth, on the whole resemble generically the Carboniferous flora, but seem to be nearly all specifically distinct. They include forms of *Calamites* (*C. gigas*), *Asterophyllites*, and ferns of the genera *Callipteris* (*C. conferta*), *Sphenopteris*, *Alethopteris*, *Neuropteris*, *Odontopteris*, with well-preserved silicified stems of tree-ferns (*Psaronius*, *Tubicaulis*). The conifer *Walchia* (*W. piniformis*) is specially characteristic. Fish remains occur sparingly (*Amblypterus*, *Palæoniscus*, *Acanthodes*), while labyrinthodonts have been met with in the Dresden district in considerable number and variety.

The Zechstein group is characterised by a suite of fossils like those of the Magnesian Limestone group of England. The Kupferschiefer contains numerous fish (*Palæoniscus Freieslebeni*, *Platysomus gibbosus*, &c.) and remains of plants (coniferous leaves and fruits and sea-weeds, *Ullmannia*, &c.). This deposit is believed to have been laid down in some enclosed sea-basin, the waters of which, probably from the rise of mineral springs connected with some of the volcanic foci of the time, were so charged with metallic salts in solution as to become unfit for the continued existence of animal life. The dead fish, plants, &c., by their decay, gave rise to reduction and precipitation of these salts

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Versteinerungen des Zechsteinsgebirge,' &c. 1848-49; C. E. Weiss, 'Fossile Flora der jungst. Steinkohlenf. und des Rothliegend.' &c. 1869-72. Much recent information will be found in the publications of the Geological Surveys of Prussia, Saxony, and Alsace-Lorraine. See, for example, E. W. Benecke and L. van Wervecke, *Mitth. Geol. Landesanst. Elsass-Lothr.* iii. part i. (1890).

[1] For an account of the Permian development in this region, see especially H. von Dechen, 'Geolog. und Palæont. Übersicht der Rheinprovinz und der Provinz Westfalen,' Bonn (1884), p. 291.

as sulphides, which thereupon enclosed and replaced the organic forms, and permeated the mud at the bottom. This old sea-floor is now the widely-extended band of copper-slate which has so long and so extensively been worked along the flanks of the Harz. After the formation of the Kupferschiefer the area must have been once more covered with clearer water, for the Zechstein Limestone contains a number of organisms, among which *Productus horridus*, *Spirifer undulatus*, *Strophalosia Goldfussi*, *Terebratula elongata*, *Camarophoria Schlotheimii*, *Schizodus obscurus*, and *Fenestella retiformis* are common. Renewed unfavourable conditions are indicated by the dolomite, gypsum, and rock-salt which succeed. Reasoning upon similar phenomena as developed in England, Ramsay has connected them with the abundant labyrinthodont footprints and other evidences of shores and land, as well as the small number and dwarfed forms of the shells in the Magnesian Limestone, and has speculated on the occurrence of a long "continental period" in Europe, during one epoch of which a number of salt inland seas existed wherein the Permian rocks were accumulated. He compares these deposits to what may be supposed to be forming now in parts of the Caspian Sea.

Some of the deposits of the Zechstein in Germany have a great commercial value. The beds of rock-salt are among the thickest in the world. At Sperenberg, near Berlin, one has been pierced to a depth of nearly 4000 feet, yet its bottom has not been reached. Besides rock-salt and gypsum there occur with those deposits thick masses of salts of potash (Carnallite) and magnesia (Kieserite) and other salts.

In Bohemia (pp. 821, 837, 846) and Moravia, where the Permian system is extensively developed, it has been divided into three groups. (1) A lower set of conglomerates, sandstones, and shales, sometimes bituminous. These strata contain diffused copper ores, and abound here and there in remains of land-plants and fishes. (2) A middle group of felspathic sandstones, conglomerates, and micaceous shales, with vast numbers of silicified tree-stems (*Araucarites*, *Psaronius*). (3) An upper group of red clays and sandstones, with bituminous shales. Eruptive rocks (melaphyre, porphyrite, &c.) are associated with the whole formation. The Zechstein is here absent. In place of the marine shells, crinoids, and corals so characteristic of that formation, the Bohemian Permian strata have yielded the remarkable series of amphibian remains already alluded to, together with abundant traces of the land of the period, such as remains of orthopterous insects, scorpions, millipedes, and a rich terrestrial flora (*Sphenopteris*, *Neuropteris*, *Odontopteris*, *Pecopteris*, *Alethopteris*, *Callipteris conferta*, *Schizopteris*, *Calamites*, *Asterophyllites*, *Sphenophyllum*, *Lepidodendron*, *Sigillaria*, *Walchia*, *Araucaryoxylon*).

Vosges.—In this region the following succession of strata has been assigned to the Permian system:—

4. Kohlbachel group of red arkoses, felspathic sandstones, shales, conglomerates, breccias, and dolomite, 500 to 600 feet, with intercalated sheets of melaphyres and tuffs.
3. Variegated tuffs and marls of Meisenbuckel.
2. Dark shales, limestones, and dolomites of Heisenstein.
1. Arkose and shale (*Callipteris conferta*), with conglomerate (sometimes 150 feet thick), containing blocks of porphyry, gneiss, quartz, &c., filling up hollows of the crystalline schists on which they lie unconformably.

The existence of volcanic action during Permian time in this region is shown by the presence of interstratified basic lavas, and by the great quantity of fragments of quartz-porphyry in the conglomerates, which have been compared to volcanic agglomerates.[1]

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[1] Benecke and Van Wervecke, *Mitth. Geol. Landesanst. Elsass-Loth.* vol. iii. (1890) p. 45; Velain, *Bull. Soc. Géol. France*, sér. 3, xiii.; Eck, 'Geogn. Karte d. Umg. von Lahr.' (1884); 'Geogn. Karte v. Schwartzwald.' (1887). A full bibliography for Alsace and Lorraine will be found in *Abth. Geol. Specialkart. v. Elsass-Lothringen*, vol. i. (1875) and vol. for 1887.

France.—Permian rocks occur in many detached areas in France. In the central plateau they are found most fully developed, resting upon and passing down into the higher parts of the Carboniferous system. They have been carefully studied in the district of Autun, where the lower part of the Permian system is represented by a mass 900 to 1000 metres thick of alternations of sandstone and shale more or less rich in hydrocarbons, with thin bands of magnesian limestone. No marine fossils occur in these strata, even the magnesian limestone containing only fresh-water organisms. From the distribution of the fossils a threefold stratigraphical subdivision of the whole series has been made. 1st, A lower group at least 150 to 200 metres thick, lying conformably upon the Coal-measures, and containing numerous ferns (*Pecopteris*, abundant), *Sigillariæ*, *Syringodendra*, *Cordaites*, a profusion of *Walchia*, large numbers of seeds or fruits, cyprids crowded in some layers of shale, an amphipod (*Nectotelson*), a number of fishes (*Palæoniscus*, *Amblypterus*, *Acanthodes*, *Pleuracanthus*), and the amphibians and reptiles already referred to (*Actinodon*, *Euchirosaurus*, *Stereorhachis*). **2nd**, A middle group about 300 metres thick, showing a cessation of the characteristically Carboniferous species of plants, and an increasing prominence of typically Permian forms. Numerous species of *Pecopteris* still occur, but *Callipteris* makes its appearance (*C. conferta*, *C. gigantea*). *Walchia* (*W. piniformis*, *W. hypnoides*), *Calamites*, *Sphenophyllum*, *Calamodendron*, and fruits abound. The animal remains resemble those of the lower group, but with the addition of *Protriton* and *Pleuroneura*. 3rd An upper group locally known as that of the "Boghead," from a workable band of bituminous shale or coal.[1] The thickness of this group is about 500 metres, the upper portion consisting of red sandstones without fossils. The flora is now markedly Permian. Pecopterid ferns are rare, and are specifically distinct from those in the group below. There is an abundance and variety of *Callipteris*, together with *Sigillaria*, abundant *Walchia* and *Asterophyllites*, *Piceites*, *Sphenophyllum*, *Carpolithes*, &c. The fauna is generally similar to that in the middle group, but less varied.[2]

In the extreme south of France, between Toulon and Cannes, Permian rocks reappear, and though occupying but a limited area, constitute some of the most picturesque features along the Mediterranean shores of the country. They consist of lower massive conglomerates, with intercalations of shale, containing *Walchia* and *Callipteris*, followed by shales, marls, red sandstones, and conglomerates. But their distinguishing feature is the enormous mass of volcanic materials associated with them. The lower conglomerates, besides their fragments of gneiss derived from the pre-Cambrian rocks of the district, contain abundant pieces of quartz-porphyry, of which rock also there are massive sheets, which rise up into the well-known group of hills forming the Esterel between Cannes and Fréjus. Besides these acid outbursts in the older part of the formation, sheets of melaphyre are found in the upper part, while dykes of nodular felsite, pitchstone, and melaphyre traverse the series.[3]

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[1] "Boghead," so named from a place in Linlithgowshire, Scotland, where the substance was first worked for making gas and oil. The so-called "Boghead" of Autun has been ascertained to contain a large quantity of the remains of gelatinous fresh-water algæ mingled with the pollen of *Cordaites*; B. Renault and E. Bertrand, *Soc. Hist. Nat. Autun*, 1892.

[2] E. Roche, *Bull. Soc. Géol. France*, sér 3, ix. (1880) p. 78. See also the series of 'Études des Gîtes Minéraux,' published by the Ministry of Public Works in France, particularly the volumes by Delafond on the Autun basin, and by Mouret on that of Brive; likewise the Memoirs by Grand' Eury already cited; Bergeron, 'Étude Géologique du Massif au sud du Plateau Central,' and *Bull. Soc. Géol. France*, 3 sér. vol. xvi. Reinach, *Zeitsch. Deutsch. Geol. Ges.* (1892) p. 23, gives a careful comparison of the French central plateau Permian rocks with those of the Saar and Nahe.

[3] F. Walleraut, 'Étude Strat. Pétrog. des Maures et de l'Esterel,' 1889. *Carte Detaill. Géol. France*, Feuille d'Antibes.

Westwards in the region of the Pyrenees, and in various parts of the Iberian peninsula, rocks believed to be Permian have been recognised. They frequently present thick masses of conglomerate, sometimes resting upon Carboniferous rocks, sometimes on formations of older date.

Alps.[1]—On both sides of the Alpine chain a zone of conglomerates and sandstones, which intervenes between the Trias and older rocks of the region, has been referred to the Permian system. The conglomerates (Verrucano conglomerate) are made up of the detritus of schistose rocks, porphyries, quartz, and other materials of the central core of the mountains. They sometimes contain sheets of porphyry, and occasionally, as at Botzen, they are replaced by vast masses of quartz-porphyry and other volcanic rocks, with tuffs and volcanic conglomerates, indicating vigorous volcanic action. An intercalated zone of shales in the lower conglomeratic and volcanic part of the series in the Val Trompia has yielded *Walchia piniformis*, *W. filiciformis*, *Schizopteris fasciculata*, *Sphenopteris tridactylites*, &c., and serves to mark the Permian age of the rocks. Eastwards, at Funfkirchen, in Hungary, in a corresponding position below the Verrucano conglomerate, a group of younger Permian plants has been found, including species of *Baiera*, *Ullmannia*, *Voltzia*, *Schizolepis*, and *Carpolithes*, nearly half of which occur also in the German Kupferschiefer. Above the conglomerate or the porphyry comes a massive red sandstone called the "Groden Sandstone," containing carbonised plant-remains. But the most distinctive and interesting feature in the Alpine development of the Permian system is found in the upper portion of the series in the southern region of Tyrol and Carinthia. The red Groden sandstone is there succeeded by beds of gypsum, rauchwacke, and dolomite, above which comes a bituminous limestone known, from the abundance of species of *Bellerophon*, as the "Bellerophon Limestone." This calcareous member is highly fossiliferous. It contains an abundant marine fauna, which includes ten species of *Bellerophon*, and species of *Nautilus*, *Natica*, *Pecten*, *Aviculopecten*, *Avicula*, *Bakevellia*, *Schizodus*, *Spirifer* (7 species), *Spirigera*, *Streptorhynchus*, *Orthis*, *Strophomena*, *Leptæna*, *Productus*, and *Fusulina*. Nearly all these are peculiar species, but the *Schizodus*, *Bakevellia*, and *Natica* connect the assemblage with that of the Zechstein.

It is interesting to trace in this Bellerophon Limestone an indication of the distribution of the more open sea of Permian time in the European area. While the Zechstein was in course of deposition in isolated Caspian-like basins across the centre of the Continent, calcareous sediments were accumulated on the floor of a wider sea which, lying to the south, stretched over the site of the present Mediterranean, eastwards across Russia and the heart of Asia. A portion of this sea-floor has been detected in Sicily, where near Palermo M. Gemmellaro has described the abundant fauna found in its limestones. Foraminifera (*Fusulina*) abound in these rocks, but their most remarkable feature is the number and variety of their cephalopods, which, besides Palæozoic types (*Goniatites*, *Orthoceratites*), comprise many new forms (17 genera and 54 species) akin to the tribe of Mesozoic Ammonites (*Adrianites*, *Agathiceras*, *Cyclolobus*, *Daraelites*, *Gastrioceras*, *Medlicottia*, *Paraprononites*, *Popanoceras*, *Stacheoceras*, *Waagenoceras*), also gasteropods (*Bellerophon*, *Pleurotomaria*, &c.) and brachiopods.[2]

Russia.[3]—The Permian system attains an enormous development in Eastern Europe.

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[1] E. Suess, *Sitzb. Akad. Wien*, lvii. (1868) pp. 230, 763; G. Stache, *Zeitsch. Deutsch. Geol. Ges.* xxxvi. (1884) p. 367; *Jahrb. k. k. Geol. Reichsanst.* xxvii. (1877) p. 271, xxviii. (1878) p. 93 (giving the fauna of the Bellerophon Limestone); *Verhand. k. k. Geol. Reichsanst.* (1888) p. 320; E. Mojsisovics, 'Die Dolomit-Riffe von Südtirol und Venetien' (1879), chap. iii.; Fraas, 'Scenerie der Alpen.'

[2] Prof. Gemmellaro, 'La Fauna dei Calcari con Fusulina,' &c. Palermo, 1887-89.

[3] See for the earliest descriptions 'Russia and Ural Mountains,' Murchison, De Verneuil, and Keyserling, 4to, 2 vols. 1845.

Its nearly horizontal strata cover by far the largest part of European Russia. They lie conformably on the Carboniferous system, and consist of sandstones, marls, shales, conglomerates, limestones (often highly dolomitic), gypsum, rock-salt, and thin seams of coal. In the lower and more sandy half of this series of strata remains of land-plants (*Calamites gigas*, *Cyclopteris*, *Pecopteris*, &c.), fishes (*Palæoniscus*), and labyrinthodonts occur, but some interstratified bands yield *Productus Cancrini* and other marine shells. The rocks are over wide regions impregnated with copper-ores. The upper half of the series consists of clays, marls, limestones, gypsum, and rock-salt, with numerous marine mollusca like those of the Zechstein (*Productus Cancrini*, *P. horridus*, *Camarophoria Schlotheimii*), but with a rather more abundant fauna, and with intercalated bands containing land-plants.

Much attention has been given in recent years to these rocks, which have now been brought into closer comparison with those of other regions. As developed on the western slope of the Ural Mountains, they have been found to consist of the following groups of strata :—

> Red clays and marls, with intercalated sandstones and limestones, almost wholly unfossiliferous, but with a few lamellibranchs resembling *Unio* (*Anthracosia*) *castor* and *U. umbonatus*. This thick group may possibly be partly or wholly Triassic.
>
> Copper-bearing sandstone, permeated with oxide and sulphide of copper, and containing species of *Calamites* (*gigas*), *Sphenopteris* (*lobata*, *erosa*), *Callipteris* (*obliqua*, *conferta*), *Noggerathia*, *Dadoxylon*, *Knorria*, &c.
>
> Marls, sandstones, and conglomerates with ill-preserved plants (which seem to be on the whole like those of the Artinsk group below), *Unio castor*, *U. umbonatus*, *U. Goldfussiana*, *Archegosaurus*, *Acrolepis*, while some of the sandy marls contain a characteristically marine fauna, *Productus Cancrini*, *P. koninckianus*, *Athyris pectinifera*, and *Spirifer lineatus*.
>
> Gypseous limestones and dolomites.
>
> Artinsk group of sandstones, conglomerates, shales, marls, limestones, and dolomites, stretching from the Arctic Ocean to the Kirgiz Steppes, and lying conformably on the Carboniferous Fusulina Limestone. This group contains a remarkably abundant and varied assemblage of fossils. The plants include species of *Calamites*, *Nöggerathia*, *Sphenopteris*, *Odontopteris*, &c. The fauna comprises a number of common Carboniferous shells such as *Productus semireticulatus*, *P. cora*, *P. longispinus*, *P. scabriculus*, *Streptorhynchus crenistria*, but with these are found many new types of cephalopods like the ammonoid forms above alluded to as occurring in the Bellerophon Limestone of the Tyrol (*Agathiceras*, *Gastrioceras*, *Medlicottia*, *Popanoceras*, *Pronorites*). About 300 species of fossils have been found in the group, of which a half also occur in the Carboniferous system, and only about a sixth in the Permian above.[1]

Asia.—The type of sedimentation found in the east and south of Europe extends into Asia. In the valley of the Araxes a limestone occurs containing *Productus horridus*, *Athyris subtilita*, and a number of the ammonoid forms above referred to; while in Bokhara other limestones occur at Darwas which from their cephalopods (*Pronorites*, *Popanoceras*, &c.) probably represent the Artinsk group of Russia. The same character of deposits and of palæontology is still more extensively developed in the Salt Range of the Punjab. In this region the ancient Palæozoic sediments with their saliferous deposits are overlain by a remarkable limestone which has yielded a large assemblage of fossils. At the base of this deposit comes a coarse conglomerate and sandstones followed by the well-known Productus Limestone.[2] The lower portions of the limestone abound in *Fusulina* with Carboniferous brachiopods (*Productus cora*, *P. semireticulatus*, *P. lineatus*,

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[1] A. Krasnopolsky, *Mém. Com. Géol. Russ.* xi. (1889) No. 1 ; A. Karpinsky, *Verhand. k. Min. Gesell. St. Petersbourg*, ix. (1874) p. 267 ; *Mém. Acad. St. Pétersbourg*, 1889 ; T. Tschernyschew, *Mém. Com. Géol. Russ.* iii. (1889) No. 4.

[2] W. Waagen, *Mem. Geol. Surv. India*, 'Salt Range Fossils,' vol. i. Productus Limestone, 1879-88.

Athyris Royssii, *Spirifer striatus*). The cephalopods are numerous and include the ammonoid types (*Cyclolobus*, *Arcestes*, *Medlicottia*, *Popanoceras*, *Xenodiscus*), as well as many Nautili, Orthoceratites, and Gyroceratites. The gasteropods include forms of *Bellerophon*, *Euomphalus*, *Holopella*, *Phasianella*, and *Pleurotomaria*. Lamellibranchs are abundantly represented by such genera as *Allorisma*, *Schizodus*, *Avicula*, *Aviculopecten*, and *Pecten*, but also with others of a distinctly Mesozoic character, as *Lima*, *Lucina*, *Loripes*, *Cardinia*, *Astarte*, and *Myophoria*. Yet with these evidences of a newer facies of molluscan life it is interesting to notice the extraordinary variety and abundance of the brachiopods, including ancient genera such as *Productus* (20 species), *Chonetes*, *Athyris*, *Orthis*, *Leptæna*, and *Streptorhynchus*, mingled with a number of new genera first met with here (*Hemiptychina*, *Notothyris*, *Lyttonia*, *Oldhamia*, &c.) Though the general aspect of this fauna is so unlike that of the Permian rocks of central Europe, the appearance of a number of Zechstein species links the limestones of northern India with the European tract. Among these are *Camarophoria humbletonensis*, *Strophalosia excavata*, *S. horrescens*, *Spiriferina cristata*.

This oceanic type of deposit, however, does not seem to extend southwards across the Indian peninsula. South of the line of the Narbada River a totally different series of sedimentary formations occurs. In that southern region the lower and middle Mesozoic marine rocks of other countries, and probably also the upper part of the Palæozoic series, are represented by a vast thickness of strata, chiefly sandstones and shales, which are probably almost entirely of fluviatile origin. To this great fresh-water accumulation the name of Gondwána system has been given by the Geological Survey of India. The lower parts of the system (Talchir and Damuda series) may perhaps be paralleled with the Permian rocks of Europe. The exceedingly coarse Talchir conglomerates contain blocks which sometimes show smoothed and striated faces, and have been compared with those of the boulder-clay as evidences of ancient glacial action in India. Among the overlying sandstones and carbonaceous layers ferns (*Gangamopteris*, *Glossopteris*, *Neuropteris*) and *Voltzia* are found. The Damuda series, estimated to be 10,000 feet thick, contains *Glossopteris*, *Gangamopteris*, *Schizoneura*, *Vertebraria*, and *Archegosaurus*. The Panchet series which succeeds is more probably Triassic, while the upper subdivisions appear to be of Jurassic age.[1]

Australia.—The "Upper Coal-measures" (Newcastle series) of New South Wales have been classed as Permian. They consist of shales, sandstones, and conglomerates, with abundant plant-remains (*Glossopteris*, *Gangamopteris*, *Vertebraria*, *Phyllotheca*, *Sphenopteris*), but with no marine shells. This group of coal-bearing strata comprises nearly all the seams of coal in the Newcastle coal-field, the lowest of which is from eight to fifteen feet thick. Another seam, near Jamberoo, is twenty-five feet thick.[2]

In Victoria certain sandstones and conglomerates (Bacchus Marsh, Grampian) have been compared with those of the Talchir series of India as possibly indicating glacial action. They contain *Gangamopteris* and *Glossopteris*.[3] In Queensland a much fuller development of Upper Palæozoic rocks has been ascertained. A great thickness of stratified deposits comprising four or five distinct formations has been named Permo-Carboniferous. In its higher portions (Bowen series) it consists of an upper fresh-water series with plants (*Sphenopteris*, *Glossopteris*), and a lower marine series containing a fauna which includes the genera *Fenestella*, *Dielasma*, *Spirifer* (*striatus*, *trigonalis*, &c.), *Derbyia*, *Productus* (*cora*, &c.), *Strophalosia*, *Chonetes*, *Aviculopecten*, *Platyschisma*, *Mourlonia*, *Bellerophon*, *Porcellia*, *Orthoceras*, *Goniatites*.[4]

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[1] Medlicott and Blanford, 'Geology of India.'

[2] C. S. Wilkinson, 'Notes on Geology of New South Wales,' Sydney, 1882, p. 51. O. Feistmantel, *Mem. Geol. Surv. N.S. Wales*, *Palæontology*, No. 3 (1890), p. 38.

[3] R. A. F. Murray, 'Geology and Phys. Geog. of Victoria,' 1887, p. 84.

[4] R. L. Jack and R. Etheridge jun. 'Geology and Palæontology of Queensland and New Guinea,' 1892, chaps. vi.-xxii.

Africa.—In the south of this continent a group of rocks occurs which presents some of the lithological and palæontological types of southern India and south-eastern Australia. At their base is a remarkable conglomerate (Dwyka) which lies unconformably on the Carboniferous quartzite and has been compared with the conglomerate of the Talchir series, but it presents many of the characters of a volcanic conglomerate.[1] It is surmounted by a series of clays or mudstones and sandstones, at least 4000 feet thick, containing plant-remains, among which *Glossopteris* is said to have been recognised. This series is unconformably surmounted by the "Kimberley shales," which pass up into the "Karoo beds." The latter are generally regarded as Triassic.

North America.—The Permian system is hardly represented at all in this part of the globe. In Kansas certain red and green clays, sandstones, limestones, conglomerates, and beds of gypsum lie conformably on the Carboniferous system, and contain a few genera and species of mollusks (*Bakevellia*, *Myalina*, &c.) which occur in the European Permian rocks. It has been urged, however, that the upper part of the Appalachian coal-field should be regarded as belonging to the Permian system. These strata, termed the "Upper Barren Measures," are upwards of 1000 feet thick. At their base lies a massive conglomeratic sandstone, above which come sandstones, shales, and limestones, with thin coals, the whole becoming very red towards the top. Professors W. M. Fontaine and I. C. White have shown that, out of 107 plants examined by them from these strata, 22 are common to the true Pennsylvanian Coal-measures and 28 to the Permian rocks of Europe; that even where the species are distinct they are closely allied to known Permian forms; that the ordinary Coal-measure flora is but poorly represented in the "Barren Measures," while on the other hand vegetable types appear of a distinctly later time, forms of *Pecopteris*, *Callipteridium*, and *Saportæa* foreshadowing characteristic plants of the Jurassic period. These authors likewise point to the indications furnished by the strata themselves of important changes in the physical condition of the American area, and to the remarkable paucity of animal life in these beds, as in the red Permian rocks of Europe. The evidence at present before us seems certainly in favour of regarding the upper part of the Appalachian coal-fields as representing the reptiliferous beds overlying the Coal-measures at Autun and their equivalents.[2] In Nova Scotia also a similar upward passage has been observed from true Coal-measures into a group of reddish strata containing Permian types of vegetation.

Passing to the western regions of the continent, we find that the vegetation which succeeded that of the Carboniferous period spread far to the west, and that it has been entombed among marine sediments. The Permian deposits traced in that direction undergo a change somewhat similar to that shown by the Carboniferous system, though on a much feebler scale. In the so-called "Wichita beds" of Texas, consisting of red and mottled clays, sandstones, and concretionary limestones resting on Coal-measures, a series of plant and animal remains has been discovered, which throws much light upon the extension of the Permian flora and fauna in North America. The plants are essentially the same as those found above the Coal-measures of Western Virginia. They include *Sphenophyllum*, *Annularia*, *Walchia*, *Odontopteris*, *Callipteris conferta*, *Callipteridium* (4 species), *Pecopteris* (8 species), and *Goniopteris*.[3] The animal-remains comprise some Carboniferous species, but also distinctively Permian types, especially some of the ammonoid cephalopods, which are now known to have so wide a range in the Old World. The cephalopods already obtained include species of *Orthoceras*, *Nautilus*, *Waagenoceras*, *Medlicottia*, *Popanoceras*, the gasteropods are represented by species of *Euomphalus*, *Bellerophon*, and *Murchisonia*, and other organisms have been detected.[1] There have also been obtained from those strata and the "Clepsydrops shales" of Illinois a number of fish, stegocephalous amphibia, and rhynchocephalous reptiles.[2]

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[1] A. H. Green, *Quart. Journ. Geol. Soc.* xliv. (1888) p. 239.

[2] "On the Permian or Upper Carboniferous Flora of W. Virginia and S.W. Pennsylvania," *Second Geol. Surv. Penn. Report*, P.P. 1880.

[3] I. C. White, *Bull. Amer. Geol. Soc.* iii. (1892) p. 217.

Spitzbergen.—The Permian sea appears to have extended far within the Arctic circle, for above the Carboniferous rocks of Spitzbergen there occurs a group of strata which contains Permian forms (*Productus*, *Streptorhynchus*, *Retzia*, *Pseudomonotis*, *Bakevellia*, &c.).[3]

PART III. MESOZOIC OR SECONDARY.

Though no geologist now admits the abrupt lines of division which were at one time believed to mark off the limits of geological systems and to bear witness to the great terrestrial revolutions by which these systems were supposed to have been terminated, nevertheless the influence of the ideas which gave life to these banished beliefs is by no means extinct. The threefold division of the stratified rocks of the terrestrial crust into Primary, Secondary, and Tertiary, or, as they are now called, Palæozoic, Mesozoic, and Cainozoic, is a relic of those ideas. This threefold arrangement is retained, however, not because each of these great periods of geological time is thought to have been separated by any marked geological or geographical episode from the period which preceded or that which followed it, but because, classification and subdivision being necessary in the acquisition of knowledge, this grouping of the earth's stratified formations into three great series is convenient. In our survey of the older members of these formations we have come to the end of the first series of fossiliferous systems, and are about to enter upon the consideration of the second. But we find no indication in the rocks of any general break in the continuity of the processes of sedimentation and of life which we have seen to be recorded among the Palæozoic rocks. On the contrary, so insensibly do the Palæozoic formations in many places merge into the Mesozoic, that not only can no sharp line be drawn between them, but it has even been proposed to embrace the strata at the top of the one series and the base of the other as parts of a single continuous system of deposits.

Nevertheless, when we look at the Mesozoic rocks as a whole, and contrast them with the Palæozoic rocks below them, certain broad distinctions readily present themselves. Whereas in the older series mechanical sediments form the prevalent constituents, piled up in masses of greywacke, sandstone, conglomerate, and shale often many thousands of feet in thickness, in the newer series limestones play a much more conspicuous part. Again, while in the Palæozoic formations a single kind of sediment may continue monotonously persistent for many hundreds or even thousands of feet of vertical depth, in the Mesozoic series, though thick accumulations of one kind of material, especially limestone, are locally developed, there is a much more general tendency towards frequent alternations of different kinds of sedimentary material, sandstones, shales, and limestones succeeding each other in rapid interchange. Another contrast between the two series is supplied by the very different extent to which they have suffered from terrestrial disturbances. Among the Palæozoic rocks it is the rule for the strata to have been thrown into various inclined positions, to have been dislocated by faults, and in many regions to have been crumpled, pushed over each other, and even metamorphosed. The exceptions to this rule are so few that they are always signalised as of special interest. Among the Mesozoic rocks, on the contrary, the original stratification-planes have usually been little deranged, faults are generally few and trifling, and it is for the most part only along the flanks or axes of great mountain-chains that extreme dislocation and disturbance can be observed. A further distinction is to be found in the relation of the two series to volcanic activity. We have seen in the foregoing chapters that every period of Palæozoic time has been marked somewhere in the Old World by volcanic eruptions, that in certain regions, such as that of the British Isles, there has been an abundant outpouring of volcanic material again and again in successive geological periods within the same limited area, and thus that masses of lava and tuff thousands of feet in thickness, and sometimes covering hundreds of square miles in extent, have been thrown out at the surface. But in the European area, with some trifling exceptions at the beginning, the whole of the Mesozoic ages appear to have been unbroken by volcanic eruptions. The felsites, rhyolites, porphyrites, diabases, basalts, and other lavas and eruptive rocks so plentiful among the Primary formations are generally absent from the Secondary series.

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[1] C. A. White, *Amer. Nat.* (1889) p. 109, *Bull. U.S. Geol. Surv.* No. 77 (1891).

[2] E. D. Cope, *Proc. Amer. Phil. Soc.* xvii. (1877-78) pp. 182, 505.

[3] B. Lundgren, *Bihang. Svensk. Vet. Akad. Handl.* xiii. (1887).

But perhaps the most striking, and certainly the most interesting, contrast between the rocks of the older and the newer series is supplied in their respective organic remains. The vegetable world undergoes a remarkable transformation. The ancient preponderance of cryptogamic forms now ceases. The antique types of Sigillaria, Stigmaria, Lepidodendron, Calamites, and their allies disappear from the land, and their places are taken by cycads and conifers, while eventually the earliest monocotyledons come as the vanguard of the rich flora of existing time. Nor are the changes less marked in the animal world. Such ancient and persistent types as the graptolites and trilobites had now wholly vanished. The crinoids, that grew so luxuriantly over the sea-floor in older time, now flourished in greatly diminished numbers, while the urchins, which had previously occupied a very subordinate position, took their place as the most conspicuous group of the Echinoderms. The brachiopods, which from the remotest time had filled so prominent a place among the mollusks, now rapidly diminished in number and variety. Among the cephalopods the Palæozoic type of the Orthoceratites was succeeded by the Mesozoic type of the Ammonites. But perhaps the most distinctive feature of the fauna was the variety and abundance of reptilian life. The labyrinthodont amphibians were replaced by many new orders, such as the Ichthyosaurs, Plesiosaurs, Ornithosaurs, Deinosaurs, and Crocodiles. It was in Mesozoic time also that the first mammals made their appearance in marsupial forms, which remained the highest types that were reached before the beginning of the Cainozoic periods.

The Mesozoic formations have been grouped in three great divisions, which, though first defined in Europe, are found to have their representative series of rocks and fossils all over the world. The oldest of these is the Trias or Triassic system, followed by the Jurassic and Cretaceous.

Section i. Triassic.

It has been already mentioned that the great mass of red rocks, which in England overlie the Carboniferous system, were formerly classed together as New Red Sandstone, but are now ranged in two systems. We have considered the lower of these under the name of Permian. The general facies of organic remains in that division is still decidedly Palæozoic. Its brachiopods and its plants connect it with the Carboniferous rocks below. Hence it is placed at the close of the long series of Palæozoic formations. When, however, we enter the upper division of the red rocks, though the general lithological characters remain in most of Europe very much as in the lower group, the fossils bring before us the advent of the great Mesozoic flora and fauna. This group therefore is put at the base of the Mesozoic or Secondary series, though in some regions, as in England, no very satisfactory line of demarcation can always be drawn between Permian and Triassic rocks. The term Trias was suggested by F. von Alberti in 1834, from the fact that in Suabia, and throughout most of Germany, the group consists of three well-marked subdivisions.[1] But the old name, New Red Sandstone, is familiarly retained by many geologists in England. The word Trias, like Dyas, is unfortunately chosen, for it elevates a mere local character into an importance which it does not deserve. The threefold subdivision, though so distinct in Germany, disappears elsewhere.

§ 1. General Characters.

As the term Trias arose in Germany, so the development of the Triassic rocks in that and adjoining parts of Europe has been accepted as the normal type of the system. There can be little doubt, however, that though this type is best known, and has been traced in detached areas over the centre and west of Europe, from Saxony and Franconia to the north of Ireland, and from Basle to the Germanic plain, reappearing even among the eastern States of North America, it must be looked upon as a local phenomenon. This assertion commends itself to our acceptance, when we reflect upon the nature of the strata of the central European Triassic basins. These rocks consist for the most part of bright red sandstones and clays or marls, often ripple-marked, sun-cracked, rain-pitted, and marked with animal footprints. They contain layers, nodules, or veinings of gypsum, beds (and scattered casts of crystals) of rock-salt, and bands or massive beds of limestone, often dolomitic. Such an association of materials points to isolated basins of deposit, or salt-lakes or inland seas, to which the outer sea found occasional access, and in which the water underwent concentration, until its gypsum and salt were thrown down. That the intervals of diminished salinity, during which the sea renewed, and perhaps maintained, a connection with the basins, were occasionally of some duration, is shown by the thickness and fossiliferous nature of the limestones.

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[1] 'Beitrag zu einer Monographie des Bunten Sandsteins, Muschelkalks, und Keupers und die Verbindung dieser Gebilde zu einer Formation,' Stuttgart, 1834, p. 324. Thirty years later the same observer published his 'Ueberblick über die Trias,' 1864, and gave a synopsis of the Triassic literature of that interval.

It is evident, however, that in this, as in all other geological periods, the prevalent type of sedimentation must have been that of the open sea. The thoroughly marine or pelagic equivalents of the red rocks of the basins have now been traced over a far wider portion of the earth's surface. In the Alps and thence eastward through the Carpathian Mountains and southern Russia into the heart of Asia and northern India, as well as southward into Italy and Spain, the deposits of the open Triassic sea are well developed. Masses of limestone and dolomite, attaining sometimes a thickness of several thousands of feet, are there replete with a characteristically marine fauna. The same fauna has been detected over a wide region of the north of Asia from Spitzbergen to Japan, the western regions of North and South America, in New Zealand, and in Southern Africa.

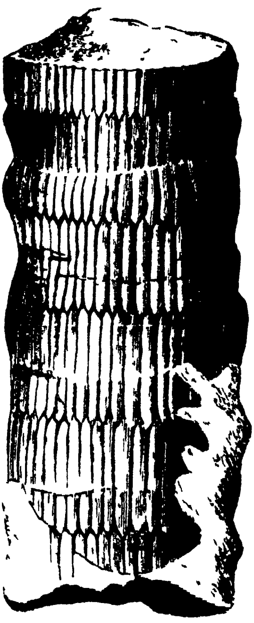
Fig. 377.—Equisetum columnare, Brongn. (½).

LIFE —The flora of the Triassic period appears to have been closely similar to that of the Permian. It consisted mainly of ferns (some of them arborescent), equisetums, conifers, and cycads. Among the ferns, a few Carboniferous genera (*Sphenopteris, Pecopteris, Cyclopteris*) still survive, together with *Glossopteris, Tæniopteris, Caulopteris*, and other old genera, but new forms have appeared (*Anomopteris, Acrostichites, Clathropteris, Lepidopteris, Merianopteris, Neuropteridium* (*Crematopteris*), *Sagenopteris*). The earliest undoubted horse-tail reeds occur in this system. Here they are represented by the two genera *Equisetum* (Fig. 377) and *Schizoneura.* The latter genus died out in the Jurassic period, but the former is still represented by twenty-five living species. The conifers are represented by *Voltzia*, the cypress-like or spruce-like twigs of which are specially characteristic organisms of the Trias (Fig. 378), and by *Albertia.* But the most distinctive feature in the flora of the earlier Mesozoic ages was the great development of cycadaceous vegetation. The most abundant genus is *Pterophyllum* ; others are *Nilssonia,* *Zamites*, *Podozamites*, *Ptilophyllum*, *Otozamites*. So typical are these plants that the Mesozoic formations have been classed as belonging to the "Age of Cycads." Calcareous algæ (*Gyroporella*, &c.) abounded in the open seas of the time and contributed to the growth of limestone reefs.

The fauna is exceedingly scanty in the red sandy and marly strata of the central European Trias, and comparatively poor in forms, though often abundant in individuals, in the calcareous zones of the same region. From the Alpine development, a much more varied suite of organisms has been disinterred. Some of the Alpine limestones are full of foraminifera (*Orbulina*, *Globigerina*), others contain numerous calcareous sponges (*Eudea*, *Verticellites*, *Peronella*, &c.) Corals abound in some localities in the same rocks, occasionally forming true reefs. Echinoderms are plentiful among the limestones, particularly crinoid-stems, of which these rocks are in some cases almost wholly composed. One of the most characteristic fossils of the Muschelkalk is the *Encrinus liliiformis* (Fig. 379). Species of urchins (*Cidaris*) are common in the Alpine Trias. An abundant fossil in some of the upper Triassic and Rhætic shales is the little phyllopod *Estheria* (Fig. 379, *b*). Long-tailed decapods, like our living shrimps and prawns, were well represented (*Penæus*, *Æger*, *Pemphyx*, &c.) The brachiopods, while showing some resemblances to those of Palæozoic time, present on the whole a great contrast to

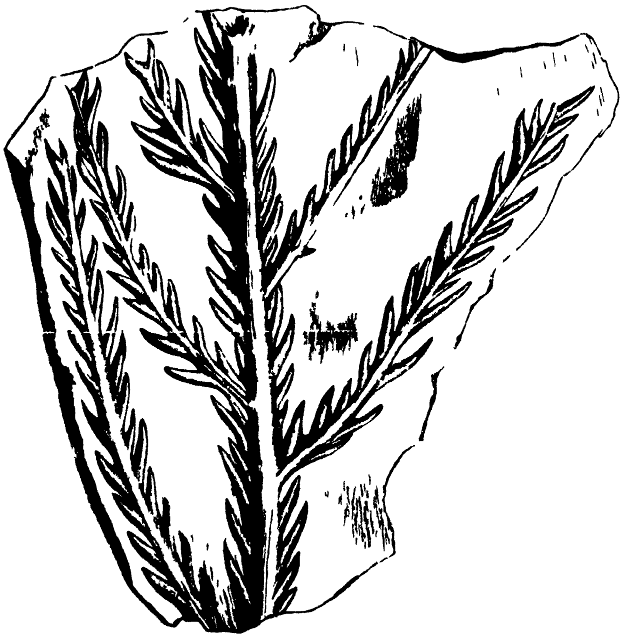

Fig. 378.—Voltzia heterophylla, Brongn.

these in their comparatively diminished numbers, and in the final disappearance of some of the ancient genera. Thus *Athyris* and *Retzia*, which survived from Upper Silurian into Triassic time, then disappeared; *Cyrtina*, which began in the Devonian period, likewise died out in the Triassic seas, while its contemporary *Spiriferina* continued to flourish until the time of the Lias. Although species of *Spiriferina*, *Athyris*, and *Retzia* are common, the two most conspicuous genera of brachiopods are *Terebratula* and *Rhynchonella*, and they continued to hold this position during the whole of the Mesozoic ages.

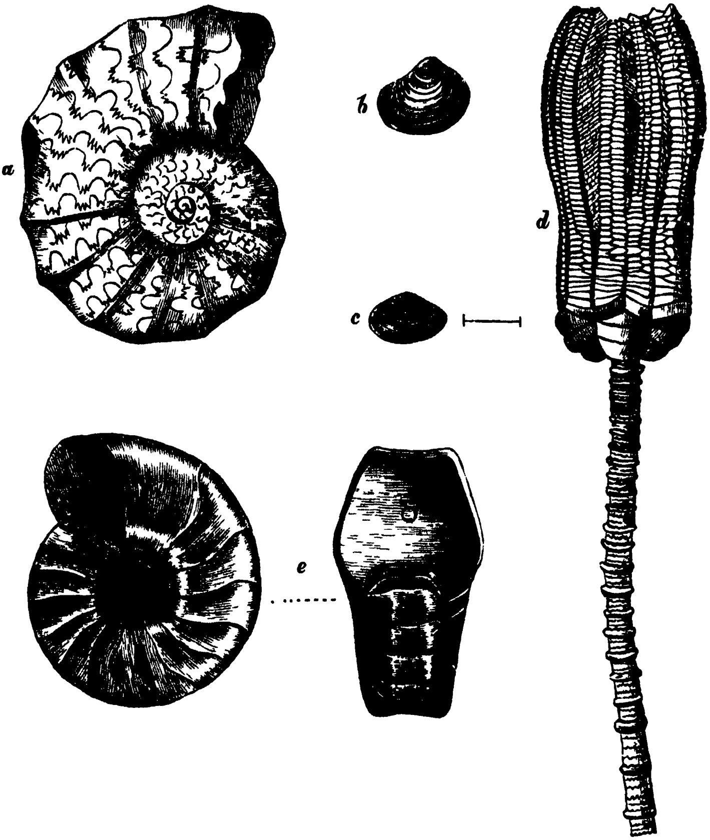

Fig. 379.—Triassic Fossils.

a, Ceratites nodosus, De Haan.; *b*, Estheria minuta, Goldf. (?); *c*, Pullastra arenicola, Strickland (nat. size and enlarged); *d*, Encrinus liliiformis, Schloth. (nat. size); *e*, Nautilus bidorsatus, Schloth. (⅛).

While the brachiopods were waning, the lamellibranchs were taking a more prominent place in the molluscan fauna, and in the Triassic seas they had already established the predominance which they have maintained down to the present day. One of the most distinctively

Triassic genera is *Myophoria*, of which there is a great abundance and variety of species. *Pecten*, *Daonella*, *Hinnites*, *Monotis*, *Lima*, *Gervillia*, *Anoplophora*, *Avicula*, *Cardium*, *Cardita*, *Megalodon*, *Nucula*, *Cassianella*, *Pullastra* (Fig. 379, *c*), likewise occur throughout the system. Among gasteropods we find representatives of some Palæozoic types (*Naticopsis*, *Loxonema*, *Macrocheilus*, *Murchisonia*), together with genera characteristic of Secondary time, and some of which even continue to live now (*Turritella*, *Cerithium*, *Chemnitzia*, *Solarium*).

In no feature is the contrast between the palæontological poverty of the German, and the richness of the Alpine Trias so marked as in the development of cephalopods in the respective regions. In the former area the nautili are represented chiefly by a few species of *Nautilus* (*N. bidorsatus*, Fig. 379, *e*), and the Ammonites by species of *Ceratites* (*C. nodosus*, Fig. 379, *a*; *C. semipartitus*). In the Alpine limestones, however, there occurs a profusion of cephalopod forms, among which a remarkable commingling of Palæozoic and Mesozoic types is noticeable. The genus *Orthoceras*, so typical of the Palæozoic rocks, has never yet been met with in the German Triassic areas; but it appears in the Alpine Trias in species which do not differ much from those of the older formations. Associated with it are many forms of the ancient and still surviving type of the *Nautilus*. It is especially interesting amid these examples of the persistence of primeval forms to notice the advent of the earliest precursors of types which played a conspicuous part in the animal life of later periods. Thus the family of the Belemnites, which appeared so prominently among the denizens of the Mesozoic seas, had its earliest known forms in the open waters of Triassic time (*Aulacoceras*, *Atractites*). Though the earliest Ammonites had appeared long before, it was not until Triassic time that this great order began to assume the importance which it maintained all through the Mesozoic ages. So long as only the German type of the Trias had been studied this early development was not known. But now besides the *Ceratites*, which also ranged into the opener Triassic waters, we have become acquainted with a remarkable variety of ammonoid types (*Arcestes*, *Didymites*, *Halorites*, *Tropites*, *Rhabdoceras*, *Ptychites*, *Sageceras*, *Trachyceras*, *Pinacoceras*, *Lobites*, *Cladiscites*, *Megaphyllites*).

The fishes of the Triassic period include teeth and spines of elasmobranchs (*Hybodus*, *Acrodus*), scales, teeth, or exoskeletons of ganoids (*Gyrolepis*, *Dapedius*, *Semionotus*, *Lepidotus*, *Nephrotus*, *Saurichthys*, *Eugnathus*) and teeth of the dipnoan genus *Ceratodus*.

One of the distinctive palæontological features of the Trias is the remarkable assemblage of amphibian and reptilian remains found in it. The ancient order of Labyrinthodonts still flourished; numerous prints of their feet have been observed on surfaces of sandstone beds, and the bones of some of them have been found (*Trematosaurus*, *Mastodonsaurus*, &c.) The rhynchocephalous reptiles, which are now almost extinct, first appear in Permian, and are well represented in Triassic rocks. Bones, and sometimes even nearly entire skeletons, of several have been discovered, the most important genera being *Telerpeton*, *Hyperoda-*

pedon, and *Rhynchosaurus*. It is noteworthy that while these various forms are by no means abundant in the Triassic system generally, they have been obtained in considerable numbers from one or two localities. In Britain the most prolific deposit for them is the pale sandstone of Elgin, in the north of Scotland, formerly believed to be Upper Old Red Sandstone. This rock contains the remains chiefly in the form of empty casts. Besides the small lizard, *Telerpeton*, described by Mantell in 1852, as well as the larger possibly allied form *Hyperodapedon*, the sandstone has recently yielded a number of new forms of Anomodonts which present a curious resemblance to those found in the South African deposit to be immediately referred to. These skulls and skeletons have been skilfully worked out and described by Mr. E. T. Newton of the Geological Survey.[1] One of them, *Gordonia*, was nearly allied to *Dicynodon* (Owen), *Geikia* was closely related to *Ptychognathus*, while *Elginia* was a remarkable many-horned animal distantly allied to *Pareiasaurus* (Owen). The South African formation, to which allusion has been made, is known as the "Karoo beds," which, extending over a vast region in the south of the continent, have furnished an interesting assemblage of vertebrate remains. Among these there occur Labyrinthodonts (*Micropholis*, *Petrophryne*, *Saurosternon*), Anomodonts (*Tapinocephalus*, *Pareiasaurus*, *Anthodon*), and a large number of genera belonging to a remarkable carnivorous order, the Theriodonts, distinguished by having three sets of teeth, like those of carnivorous mammals (*Lycosaurus*, *Tigrisuchus*, *Cynodracon*, &c.) There were likewise examples of Dicynodonts, characterised by having no teeth, or by a single tusk-like pair, the jaws being probably prolonged into a horny beak. The limbs of these creatures were well developed, and the animals probably walked on the land (*Dicynodon*, *Oudenodon*, &c.)[2] The earliest deinosaurs yet known occur in this system (*Thecodontosaurus*, *Teratosaurus*, *Palæosaurus*, *Cladyodon*, *Plateosaurus* (*Zanclodon*), *Ammosaurus*, *Anchisaurus*, &c.)[3] These long-extinct types of reptilian life presented characters in some measure intermediate between those of the ostriches and true reptiles, and their size and unwieldiness gave them a resemblance to the elephants and rhinoceroses of modern times. They appear to have walked mainly on their strong hind legs, the prints of their hind feet occurring in great abundance among the red sandstones of Connecticut. Many of them had three bird-like toes, and left footprints quite like those of birds. Others had four or even five toes, and attained an enormous size, for a single footprint sometimes measures twenty inches in length.

The ichthyosaurs and plesiosaurs, which played so foremost a

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[1] *Phil. Trans.* 1893.

[2] Owen's 'Catalogue of Fossil Reptilia of South Africa,' Brit. Museum, 1876.

[3] See on deinosaurs of the Trias, Huxley, *Q. J. Geol. Soc.* xxvi. 32. In the year 1877, a slab of the "Stubensandstein" near Stuttgart was obtained, in which were twenty-four individuals of "a mailed bird-lizard," named *Aëtosaurus*, probably a deinosaur with lacertilian characters. O. Fraas, *Jahrb. Ver. Nat. Würtemberg*, xxxiii. (1877). For the Triassic deinosaurs of Connecticut see Marsh, *Amer. Journ. Sci.* xxxvii. (1889) p. 331; xlii. (1891) p. 267; xliii. (1892) p. 542; xlv. (1893) p. 169.

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pedon, and *Rhynchosaurus*. It is noteworthy that while these various forms are by no means abundant in the Triassic system generally, they have been obtained in considerable numbers from one or two localities. In Britain the most prolific deposit for them is the pale sandstone of Elgin, in the north of Scotland, formerly believed to be Upper Old Red Sandstone. This rock contains the remains chiefly in the form of empty casts. Besides the small lizard, *Telerpeton*, described by Mantell in 1852, as well as the larger possibly allied form *Hyperodapedon*, the sandstone has recently yielded a number of new forms of Anomodonts which present a curious resemblance to those found in the South African deposit to be immediately referred to. These skulls and skeletons have been skilfully worked out and described by Mr. E. T. Newton of the Geological Survey.[1] One of them, *Gordonia*, was nearly allied to *Dicynodon* (Owen), *Geikia* was closely related to *Ptychognathus*, while *Elginia* was a remarkable many-horned animal distantly allied to *Pareiasaurus* (Owen). The South African formation, to which allusion has been made, is known as the "Karoo beds," which, extending over a vast region in the south of the continent, have furnished an interesting assemblage of vertebrate remains. Among these there occur Labyrinthodonts (*Micropholis*, *Petrophryne*, *Saurosternon*), Anomodonts (*Tapinocephalus*, *Pareiasaurus*, *Anthodon*), and a large number of genera belonging to a remarkable carnivorous order, the Theriodonts, distinguished by having three sets of teeth, like those of carnivorous mammals (*Lycosaurus*, *Tigrisuchus*, *Cynodracon*, &c.) There were likewise examples of Dicynodonts, characterised by having no teeth, or by a single tusk-like pair, the jaws being probably prolonged into a horny beak. The limbs of these creatures were well developed, and the animals probably walked on the land (*Dicynodon*, *Oudenodon*, &c.)[2] The earliest deinosaurs yet known occur in this system (*Thecodontosaurus*, *Teratosaurus*, *Palæosaurus*, *Cladyodon*, *Plateosaurus* (*Zanclodon*), *Ammosaurus*, *Anchisaurus*, &c.)[3] These long-extinct types of reptilian life presented characters in some measure intermediate between those of the ostriches and true reptiles, and their size and unwieldiness gave them a resemblance to the elephants and rhinoceroses of modern times. They appear to have walked mainly on their strong hind legs, the prints of their hind feet occurring in great abundance among the red sandstones of Connecticut. Many of them had three bird-like toes, and left footprints quite like those of birds. Others had four or even five toes, and attained an enormous size, for a single footprint sometimes measures twenty inches in length.

The ichthyosaurs and plesiosaurs, which played so foremost a part in the reptilian life of Mesozoic time, had their Triassic forerunners (*Ichthyosaurus*, *Nothosaurus*, *Simosaurus*, *Neusticosaurus*). Of higher grade were the earliest types of crocodiles, the remains of which have been detected in Triassic rocks. They belong to an extremely generalised type, and appear to have been widely distributed. *Stagonolepis* occurs among the other reptilian remains at Elgin,[1] while *Phytosaurus* (*Belodon*) has been obtained in Germany, India and North America.

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[1] *Phil. Trans.* 1893.

[2] Owen's 'Catalogue of Fossil Reptilia of South Africa,' Brit. Museum, 1876.

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It has been supposed that evidence of the existence of Triassic birds is furnished by the three-toed footprints above referred to. But probably these are mostly, if not entirely, the tracks of deinosaurs, the absence of two pairs of prints in each track being accounted for by the bird-like habit of the animals in the use of their hind feet in walking. One of the most noteworthy facts in the palæontology of the Trias is the occurrence in this system of the first relics of mammalian life. These consist of detached teeth and lower jaw-bones, referred to small marsupial animals allied to the *Myrmecobius*, or Banded Ant-eater of New South Wales. The European genus is *Microlestes* (*Hypsiprymnopsis*). In the Trias of North Carolina an allied form has been described under the name of *Dromatherium*.

§ 2. Local Development.

Britain.[2]—Triassic rocks occupy a large area of the low plains in the centre of England, ranging thence northwards along the flanks of the Carboniferous tracts to Lancaster Bay, and southwards by the head of the Bristol Channel to the south-east of Devonshire. They have been arranged in the following subdivisions :—

Rhætic.[3]	Penarth beds.—Red, green, and grey marls, black shales, and "White Lias" (20 feet or less up to 150 feet).
Upper Trias or Keuper.	Upper Keuper or New Red Marl.—Red and grey shales and marls, with beds of rock-salt and gypsum (800 to 3000 feet).
	Lower Keuper Sandstone.—Thinly laminated micaceous sandstones and marls (waterstones), passing downwards into white, brown, or reddish sandstones, with a base of conglomerate or breccia (150 to 250 feet).
Lower Trias or Bunter (1000 to 2000 feet).	Upper Mottled Sandstone.—Soft bright red and variegated sandstones, without pebbles (200 to 700 feet).
	Pebble-beds.—Harder reddish-brown sandstones with quartzose pebbles, passing into conglomerate; with a base of calcareous breccia (60 to more than 1000 feet).
	Lower Mottled Sandstone.—Soft bright red and variegated sandstone, without pebbles (80 to 650 feet).

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[1] On the Crocodilian remains of the Elgin Sandstone see Huxley, *Quart. Journ. Geol. Soc.* 1859; *Mem. Geol. Surv.* Monograph iii. 1877.

[2] See E. Hull, "Permian and Triassic Rocks of England," *Geological Survey Memoirs*, 1869; H. B. Woodward, *Geol. Mag.* 1874, p. 385; "Geology of East Somerset and Bristol Coal-fields," *Mem. Geol. Survey*, 1876; Ussher, *Q. J. Geol. Soc.* xxxii. 367; xxxiv. 459; *Geol. Mag.* 1875, p. 163; *Proc. Somerset. Arch. Nat. Hist. Soc.* xxxv. (1889); Etheridge, *Q. J. Geol. Soc.* xxvi. 174; A. Irving, *Geol. Mag.* 1874, p. 314; 1887, p. 309; *Quart. Journ. Geol. Soc.* 1888, p. 149; W. T. Aveline, *op. cit.* 1877, p. 380; J. G. Goodchild, *Trans. Cumberl. Westmorel. Assoc.* xvii. (1891-92).

[3] The term "Rhætic" is derived from the Rhætian Alps, where the rocks so named are well developed. "Bunter" and "Keuper" are terms borrowed from Germany, the first was

Like the Permian red rocks below, the sandstones and marls of the Triassic series are almost barren of organic remains. Extraordinary differences in the development of their several members occur, even within the limited area of England, as may be seen from the subjoined table, which shows the variations in thickness from north-west to south-east:—

		Lancashire and W. Cheshire.	Staffordshire.	Leicestershire and Warwickshire.
		Feet.	Feet.	Feet.
Keuper.	Red marl	3000	800	700
	Lower Keuper sandstone . .	450	200	150
Bunter.	Upper mottled sandstone . .	500	50–200	absent
	Pebble-beds	500–750	100–300	0–100
	Lower mottled sandstone . .	200–500	0–100	absent

Hence we observe that, while towards the north-west the Triassic rocks attain a maximum depth of 5200 feet, they rapidly come down to a fifth or sixth of that thickness as they pass towards the south-east. South-westwards, however, they swell out in Devon and Somerset to probably not less than 2500 or 3000 feet.[1] Recent borings in the south-eastern counties show the Trias to be there generally absent.[2] The main source of supply of the sediment which formed the material of the Triassic deposits probably lay towards the north or north-west. The pebble-beds, besides local materials, contain abundant rolled pebbles of quartz, which have evidently been derived from some previous conglomerate, probably from some of the Old Red Sandstone masses now removed or concealed. The Trias rests with a more or less decided unconformability on the rocks underneath it, so that, although the general physical conditions as regards climate, geography, and sedimentation, which prevailed in the Permian period, still continued, terrestrial movements had, in the meanwhile, takén place, whereby the Permian sediments were generally upraised and exposed to denudation. Hence the Trias rests now on Permian, now on Carboniferous, and sometimes even on Cambrian rocks. Moreover, the upper parts of the Triassic series overlap the lower, so that the Keuper groups repose successively on Permian and Carboniferous rocks.

The Bunter series is singularly devoid of organic remains. The rolled fragments in the pebble-beds have yielded fossils at Budleigh Salterton, on the southern coast of Devonshire, proving that Silurian and Devonian rocks were exposed within the area from which the materials of these strata were derived. The peculiar quartzites of the Budleigh Salterton pebbles do not seem to have come from any British rocks now visible, but rather to have been derived from the north-west of France.[3] A marked characteristic of the Bunter series in central England is its capacity for holding water, whence it is an important source of water-supply.

At the base of the Keuper series, in the region of the Mendip Hills, a remarkable littoral breccia or conglomerate occurs. Over Carboniferous Limestone it consists mainly of limestone, and is precisely like "brockram" (p. 847), but in the slaty tracts of Devonshire, the fragments are of slate, porphyry, granite, &c. Its matrix being sometimes dolomitic, it has been called the Dolomitic conglomerate; but it occasionally passes into

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taken by Werner from the variegated (German, *bunt*) colours of the strata, the second is a local miner's term.

[1] Ussher, *Q. J. Geol. Soc.* xxxii. 392.

[2] Red strata in the deep boring at Richmond are believed by Prof. Judd to be Triassic. Mr. Whitaker regards as Trias similar rocks found under Kentish Town and Crossness near London.

[3] For an account of their included fossils see Davidson, *Palæontograph. Soc.* 1881.

a magnesian limestone. It represents the shore deposits of the Trias salt-lake or inland sea, and, as it lies on many successive horizons, we see that the conditions for its formation persisted during the subsidence by which the Mendips and other land of this region were gradually depressed and obliterated under the red sandstones and marls (see Figs. 219, 220, 221).[1] The Dolomitic conglomerate averages 20 feet in thickness, but here and there rises into cliffs 40 or 50 feet high. It has yielded two genera of deinosaurs (*Palæosaurus*, *Thecodontosaurus*).[2] Some geologists have regarded this band of rock as an English representative of the German Muschelkalk. But the manner in which it ascends along what was the margin of the Triassic land shows it to be a local base occupying successive horizons in the red rocks. There is no equivalent of the Muschelkalk in Britain, unless the middle division of the Devonshire Trias can be so regarded.[3]

The lower Keuper group is composed of red and white sandstones with occasional lenticular bands of coarser material, and like the corresponding strata in the Bunter group, is generally unfossiliferous, but has furnished many amphibian footprints. The surfaces of the sandstone-beds are likewise impressed with rain-drops and are marked with desiccation-cracks and ripple-marks, suggestive of flat shores exposed to the air.

In the upper Keuper group the sediments were generally muddy and now appear as red and variegated marls with occasional partings of sandstone or bands of dolomite or of gypsum. Among these strata are beds of rock-salt varying from a few inches to more than 100 feet in thickness. The marly character of the upper Keuper is a distinguishing feature of the group from the south of Scotland to the south of Devonshire, and from Antrim to the east of Yorkshire. Throughout this wide area cubical casts of salt (chloride of sodium) are not infrequent, though this substance is only workable at a few places (Antrim, Cheshire, Middlesbrough[4]). The salt is chiefly obtained by dissolving the material underground and pumping up the brine, very little being now actually mined. The rock-salt as it occurs intercalated in the marls is a crystalline substance, usually tinged yellow or red from intermixture of clay and peroxide of iron, but is tolerably pure in the best parts of the beds, where the proportion of chloride of sodium is as much as 98 per cent. Through the bright red marls with which the salt is interstratified there run thin seams of rock-salt, also bands of gypsum, somewhat irregular in their mode of occurrence, sometimes reaching a thickness of 40 feet and upwards.

The paucity of organic remains in the English Keuper indicates that the conditions for at least animal life must have been extremely unfavourable in the waters of the ancient Dead Sea wherein these red rocks were accumulated. The land possessed a vegetation which, from the fragments yet known, seems to have consisted in large measure of cypress-like coniferous trees (*Voltzia*, *Walchia*), with calamites on the lower more marshy grounds. The red marl group contains in some of its layers numerous valves of the little crustacean *Estheria minuta*, and a solitary species of lamellibranch, *Pullastra arenicola*. A number of teeth, spines, and sometimes entire skeletons of fish have been obtained (*Dipteronotus cyphus*, *Palæoniscus superstes*, *Hybodus Keuperi*, *Acrodus minimus*, *Sphenonchus minimus*, &c.) The bones, and still more frequently the footprints, of labyrinthodont and even of saurian reptiles occur in the Keuper beds —*Labyrinthodon* (4 species), *Cladyodon Lloydii*, *Hyperodapedon*, *Palæosaurus*, *Zanclodon* (*Teratosaurus*), *Thecodontosaurus*, *Rynchonosaurus*, and footprints of *Cheirotherium*. The remains of the small marsupial *Microlestes* have likewise been discovered in the highest beds sometimes taken as the base of the Rhætic series.

At the top of the Keuper marl certain thin-bedded strata form a gradation upwards into the base of the Jurassic system. As their colours are grey, blue, and black, and contrast with the red and green marls below, they were formerly classed without hesitation in the Jurassic series. Egerton, however, showed that, from the character of the fish remains found in the "bone-bed" of the black shales, they had more palæontological affinity with the Trias than with the Lias. Subsequent research, particularly among the Rhætian Alps and elsewhere on the Continent, brought to light a great series of strata of intermediate characters between the previously recognised Trias and Lias. These results led to renewed examination of the so-called beds of passage in England (Penarth beds),[1] which were found to be truly representative of the massive formations of the Tyrolese and Swiss Alps. They are therefore now known as Rhætic (sometimes as Infra-Lias), and are usually classed as the uppermost member of the Trias, but offering evidence of the gradual approach of the physical geography and characteristic fauna and flora of the Jurassic period.

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[1] De la Beche, *Mem. Geol. Survey*, i. p. 240. H. B. Woodward, "Geology of East Somerset and Bristol Coal-fields," *Mem. Geol. Survey*, 1876, p. 53.

[2] Etheridge, *Q. J. Geol. Soc.* xxvi. 174.

[3] Ussher, *op. cit.* xxxiv. p. 469.

[4] T. Hugh Bell on salt deposits of Middlesbrough, *Proc. Cleveland Inst. Engin.* Session 1882-83.

The Rhætic (Penarth) beds occur as a continuous though thin band at the top of the Trias, throughout the British area. They extend from the coast of Yorkshire across England to Lyme Regis on the Dorsetshire shores.[2] They occur in scattered patches up the west of England, and on both sides of the Bristol Channel, and they may be detected even in the north of Scotland. Their thickness, on the average, is probably not more than 50 feet, though it rarely increases to 150 feet. In the south-west of England, they consist of the following subdivisions in descending order:—

> White Lias—composed of an upper hard limestone (Sun-bed or Jew-stone, 6 to 18 inches) with *Modiola minima* and *Ostrea liassica*; and a lower group of pale limestones (10 to 20 feet) with the same fossils and *Cardium phillipianum* (*rhæticum*), *Monotis decussata*. The Cotham Stone or Landscape Marble (4 to 8 inches) is a hard compact limestone, with dendritic markings, lying at the base of these calcareous strata. At Aust it has yielded elytra of Coleoptera, wings of insects, and scales and perfect specimens of the fishes *Legnonotus cothamensis*, *Pholidophorus Higginsi*.
>
> Black paper-shales (10 to 15 feet), finely laminated and pyritous, with selenite and fibrous calcite ("beef") and one or more seams of ferruginous and micaceous sandstone (bone-bed) containing remains of fish and saurians. Some of the shales yield *Avicula* (*Cassianella*) *contorta*, *Cardium phillipianum* (*rhæticum*), *Pecten valoniensis* (= *Avicula contorta* zone).
>
> Green and grey Marls (20 to 30 feet), with alabaster, celestine, and sometimes pseudomorphs of rock-salt; generally unfossiliferous, but yielding *Microlestes*. These Marls form properly the top of the Trias, the bone-bed above serving as a convenient base for the Rhætic beds.

A bone-bed similar to that in the foregoing section reappears on the same horizon in Hanover, Brunswick, and Franconia. Among the reptilian fossils are some precursors of the great forms which distinguished the Jurassic period (*Ichthyosaurus* and *Plesiosaurus*). The fishes include *Acrodus minimus*, *Ceratodus altus* (and five other species), *Hybodus minor*, *Nemacanthus monilifer*, &c. Some of the lamellibranchs (Fig. 380) are specially characteristic; such are *Cardium phillipianum* (*rhæticum*), *Avicula* (*Cassianella*) *contorta*, *Pecten valoniensis*, and *Pullastra arenicola* (Fig. 379).

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[1] So named from their being well developed in the cliffs of Penarth on the Glamorganshire coast. Bristow, *Brit. Assoc.* 1864, sects. p. 50; *Geol. Surv. Vertical Sections*, sheets 47, 48.

[2] Strickland, *Proc. Geol. Soc.* iii. part ii. p. 585; H. W. Bristow, *Geol. Mag.* i. (1864) p. 236; T. Wright, *Quart. Journ. Geol. Soc.* xvi. p. 374; C. Moore, *op. cit.* xvi. p. 483; xxiii. p. 459; xxxvii. pp. 67, 459; W. B. Dawkins, xx. p. 396; E. B. Tawney, xxii. p. 69; P. B. Brodie, p. 93; F. M. Burton, xxiii. p. 315; W. J. Harrison, xxxii. p. 212; P. M. Duncan, xxiii. p. 12; J. W. Davis, xxxvii. p. 414; E. Wilson, xxxviii. p. 451; H. B. Woodward, "Geology of E. Somerset and Bristol Coal-fields," *Mem. Geol. Survey*, p. 69; *Proc. Geol. Assoc.* x. (1888).

Central Europe.—The Trias is one of the most compactly distributed geological formations of Europe. Its main area extends as a great basin from Basel down to the plains of Hanover, traversed along its centre by the course of the Rhine, and stretching from the flanks of the old high grounds of Saxony and Bohemia on the east across the Vosges Mountains into France, and across the Moselle to the flanks of the Ardennes. This must have been a great inland sea, out of which the Harz Mountains, and the high grounds of the Eifel, Hunsdrück, and Taunus probably rose as islands. To the westward of it, the Palæozoic area of the north of France and Belgium had been raised up into land.[1] Along the margin of this land, red conglomerates, sandstones, and clays were deposited, which now appear here and there reposing unconformably on the older formations. Traces of what were probably other basins occur eastward in the Carpathian district, in the west and south-east of France, and over the eastern half of the Spanish peninsula. But these areas have been considerably obscured, sometimes by dislocation and denudation, sometimes by the overlap of more recent accumulations. In the region between Marseilles and Nice, Triassic rocks cover a considerable area. They contain feeble representatives of the *Grès bigarré* or Bunter beds, and of the *Marnes irisées* or Keuper division, separated by a calcareous zone believed to be the equivalent of the Muschelkalk of Germany. Their highest platform, the Rhætic or *Infra-Lias*, contains a shell-bed abounding in *Avicula contorta*, and is traceable throughout Provence.[2]

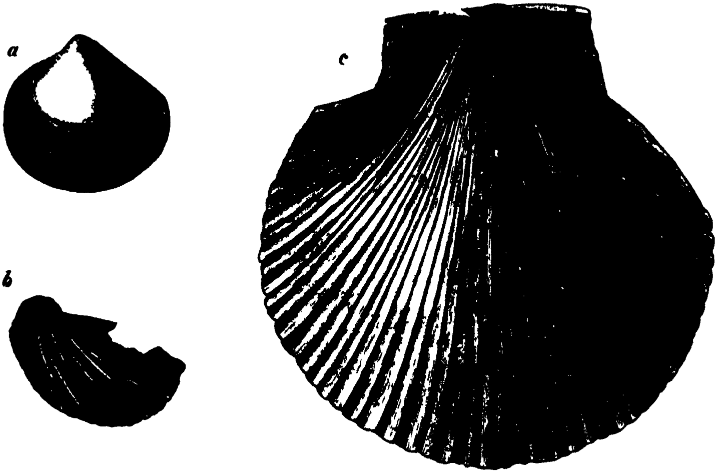

Fig. 380.—Rhætic Fossils.
a, Cardium phillipianum (rhæticum, Merian.); b, Avicula (Cassianella) contorta, Portlock; c, Pecten valoniensis, Defrance.

In the great German Triassic basin[3] the deposits are as shown in the subjoined table:—

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[1] This land, according to MM. Cornet and Briart, rose into peaks 16,000 to 20,000 feet high! (*Ann. Soc. Géol. Nord*, iv.)

[2] Hébert, *Bull. Soc. Géol. France* (2e sér.) xix. p. 100. Dieulafait, *Ann. Sci. Géol.* i. p. 337.

[3] E. Weiss, *Zeitsch. Deutsch. Geol. Ges.* xxi. (1869) p. 837; C. W. Gümbel, 'Geognostische Beschreibung des Konigreichs Bayern,' iii. (1879) chap. xv.; F. Roemer, 'Geologie von Oberschlesien,' 1870, p. 122; E. W. Benecke, 'Über die Trias in Elsass-Lothringen und Luxemburg,' *Abh. Geol. Specialkarte Elsass-Lothr.* i. part iv. (1877); G. Meyer,

Rhætic.

Rhætic (Rhät, Infra-Lias).—Grey sandy clays and fine-grained sandstones, containing *Equisetum*, *Asplenites*, and cycads (*Zamites*, *Pterophyllum*), sometimes forming thin seams of coal—*Cardium phillipianum* (*rhæticum*), *Avicula* (*Cassianella*) *contorta*, *Estheria minuta*, *Nothosaurus*, *Trematosaurus*, *Belodon*, and *Microlestes antiquus*.[1]

Keuper.

Keupermergel, Gypskeuper.—Bright red, green and mottled marls, with an underlying set of beds of gypsum and rock-salt. In some places where sandstones appear they contain numerous plants (*Equisetum columnare*, *Pterophyllum*, &c.), and labyrinthodont and fish remains[2] (300 to 1000 feet).

Lettenkohle, Kohlenkeuper.—Grey sandstones and dark marls and clays, with abundant plants, sometimes forming thin seams of an earthy hardly workable coal (Lettenkohle), about 230 feet. The plants include, besides those above mentioned, the conifers *Araucarioxylon thuringicum*, *Voltzia heterophylla*, &c. A few shells have been obtained from this group, especially from a band of dolomite at its upper limit (*Lingula tenuissima*, *Myophoria Goldfussi*, *M. transversa*, *Anoplophora*, *Gervillia*). Some of the shales are crowded with small phyllopod crustacea (*Estheria minuta*, also *Bairdia*). Remains of fish (*Acrodus*, *Hybodus*, *Ceratodus*) and of the *Mastodonsaurus Jægeri* and *Nothosaurus* have been obtained.

Muschelkalk.

Upper Limestone, capable of subdivision into two groups, a lower hard encrinite limestone (Trochitenkalk) and an upper group of thin limestone with argillaceous partings, known as the Nodosus group from the abundance of *Ceratites nodosus* (200 to 400 feet). In some regions a third still higher group of dolomites and limestones is called the Trigonus group from the prevalence in it of *Trigonodus Sandbergeri*. The upper Muschelkalk is by far the most abundantly fossiliferous division of the German Trias. Among its fossils, *Nautilus bidorsatus*, *Lima striata*, *Myophoria vulgaris*, *Trigonodus Sandbergeri*, and *Terebratula vulgaris* are specially characteristic, with *Encrinus liliiformis* in the lower and *Ceratites nodosus* in the upper part of the rock. Some parts of the lower limestones are almost wholly made up of crinoid stems.

Middle Limestone and Anhydrite, consisting of dolomites with anhydrite, gypsum, and rock-salt. Nearly devoid of organic remains, though bones and teeth of saurians have been found (200 to 400 feet).

Lower Limestone (Wellenkalk), consisting of limestones and dolomites (Wellendolomite), with in the upper part bands of porous limestone known as Schaumkalk (160 to 500 feet). This zone is on the whole poor in fossils, save in the limestone bands, some of which form a lower zone full of *Encrinus liliiformis*, while a higher zone is characterised by *Myophoria orbicularis*. The upper portion of the limestone, however, is highly fossiliferous, and has yielded a number of brachiopods (*Spiriferina fragilis*, *S. hirsuta*, *Athyris trigonella*, *Terebratula vulgaris*, *T. angusta*, numerous lamellibranchs, especially the widespread genus *Myophoria* (*M. vulgaris*, *elegans*, *cardissoides*), *Gervillia costata*, *Monotis Alberti*, and some ammonites (*Beneckeia*, *Ceratites*, &c.)

Mittheil. Com. Geol. Landes-Untersuch. i. part i. (1886); H. Bucking and E. Schumacher, *op. cit.* ii. part ii. (1889); E. W. Benecke and L. van Wervecke, *op. cit.* iii. part i. (1890); and the Jahrbuch of the Prussian Geological Survey. Detailed measured sections of the Muschelkalk and Lettenkohle in Franconia are given by F. v. Sandberger, *Verh. Phys. Med. Ges. Würzburg*, xxvi. (1892) No. 7. S. Passarge, 'Das Röth im östlichen Thüringien,' Jena, 1891.

[1] The *Avicula contorta* zone (see Dr. A. von Dittmar, 'Die Contorta-Zone,' Munich, 1864) ranges from the Carpathians to the north of Ireland and from Sweden to the hills of Lombardy. In northern and western Europe, it forms part of a thin littoral or shallow-water formation, which over the region of the Alps expands into a massive calcareous series, that accumulated in a deeper and clearer sea. It is well developed also in northern Italy. See Stoppani, 'Géologie et Paléontologie des Couches à Avicula Contorta en Lombardie,' Milan, 1881.

[2] It is deserving of notice that while in the pelagic or Alpine facies of the Trias fish-

Bunter.

Upper (Röth).—Red and green marls, with gypsum in the lower part, and sometimes beds of rock-salt (250 to 300 feet). Occasional bands of dolomite (*Rhizocorallium* dolomite of Thuringia), yield a number of fossils (*Rhizocorallium jenense*, probably a sponge, *Myophoria costata*, *M. vulgaris*, *Gervillia socialis*, *Myacites mactroides*, the Ammonite *Beneckeia tenuis*). The *Myophoria* is specially characteristic. The plants of this stage consist chiefly of *Voltzia*, with ferns and horse-tails (*Anomopteris*, *Equisetum*).

Middle.—Coarse-grained sandstones (1000 feet), sometimes incoherent, with wayboards of *Estheria*-shale; amphibian footprints and remains of labyrinthodonts.

Lower.—Fine reddish argillaceous false-bedded sandstone (Grès des Vosges) several hundred feet thick, often micaceous and fissile, with occasional interstratifications of dolomite and of the marly oolitic limestone called "Rogenstein." Fossils extremely scarce; *Estheria minuta* occurs in some layers.

The Bunter division, in the north and centre of Germany, lies conformably on and passes insensibly into the Zechstein. Except in the dolomite beds of the Röth, it is usually barren of organic remains. The plants already known include *Equisetum arenaceum*, one or two ferns, and a few conifers (*Albertia* and *Voltzia*). The lamellibranch *Myophoria costata* is found in the upper division all over Germany. Numerous footprints occur on the sandstones, and the bones of labyrinthodonts as well as of fish have been obtained.

In the Vosges, the Bunter (Grès bigarré, Vosgian) consists of (1) a lower coarse red unfossiliferous sandstone (Grès des Vosges) resting conformably on the red Permian sandstone and marked by the frequent crystalline condition of its quartz-grains (crystalline sandstone, p. 132); also by its quartz-conglomerates, which occasionally reach a thickness of more that 1600 feet; (2) an upper series of red sandstones, surmounted by marls, forming the *Grès bigarré*, and containing among other fossils *Voltzia*, *Albertia*, *Equisetum arenaceum*, *Myophoria*, *Nothosaurus Schimperi*, *Menodon plicatus*, *Odontosaurus Voltzii*, *Mastodonsaurus waslenensis*. The Muschelkalk in the same region is a compact grey limestone capable of subdivision into three zones, as in Germany, while the Keuper (Marnes irisées) presents a characteristic assemblage of bright red and green mottled argillaceous marls.[1]

Scandinavia.[2]—Though fragmentary remains of the terrestrial flora that clothed the land which surrounded the German Triassic inland sea not infrequently occur, it is on the north side of the basin that the most abundant traces have been recovered of the vegetation of this period. Above reddish saliferous rocks, presumably Triassic, there come in southern Sweden certain light grey and yellow strata, which, from the occurrence of *Avicula contorta* and other fossils in them, are assigned to the Rhætic stage, though possibly their higher members may be Jurassic. They attain in some places a thickness of 500 to 800 feet, and cover about 250 square miles. They have been divided into a lower fresh-water group, with workable coal-seams, but no marine fossils, and an upper marine group, with only poor coals, but with numerous marine

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remains are on the whole scarce, and only occur in numbers at a few places, they are widely distributed and tolerably abundant throughout the German Trias. See O. Jaekel, *Abhand. Geol. Specialkart. Elsass-Lothr.* iii. Heft iv. (1889).

[1] Benecke, *Abhandl. Specialkarte Elsass-Lothringen*, 1877; Lepsius, *Z. Deutsch. Geol. Ges.* 1875, p. 83.

[2] See Hébert, *Ann. Sci. Géol.* 1869, No. 1; *Bull. Soc. Géol. France* (2), xxvii. (1870), p. 366; *Memoirs of the Geological Survey of Sweden*, especially Nathorst "Om Floran Skånes Kolförande Bildningar," 1878, 1879; E. Erdmann, "Beskrifning till Kartbladet Helsingborg," 1881, p. 42; G. Lindström, *op. cit.* "Kartbladet Engelholm," 1880; also Nathorst, "Bidrag till Sveriges fossila Flora," *K. Vet. Akad. Handl. Stockholm*, xiv. xvi.; Lundgren, *Geol. Fören. Stockholm Förh.* 1880.

organisms (*Ostrea, Pecten, Avicula,* &c.). In the coal-bearing strata clay-ironstones occur, and seams of fireclay underlie the coals. Nathorst and Lundgren have brought to light 150 species of plants from these beds—a larger number than the whole of the Triassic flora of other countries. At Bjuf they include 36 species of ferns, 36 cycads, 15 conifers, and 1 monocotyledon. The subjoined grouping of the Swedish Triassic rocks has been given by Lundgren:—

Arieten-Lias.
Cardinia Lias.
Younger Rhætic, Zone of *Nilssonia polymorpha.*
Rhætic . . { Pullastra bed.
Zone of *Thaumatopteris Schenki.*
Zone of *Equisetum gracile.*
Zone of *Lepidopteris Ottonis.*
Older Rhætic . Zone of *Camptopteris spiralis.*
Keuper.

Alpine Trias.[1]—In the western Alps, certain lustrous schists, with gypsum, anhydrite, dolomite and rock-salt, lie underneath the Jurassic series, and are referred to the Trias. On the Italian side, they swell out to great proportions, reaching a thickness of more than 13,000 feet along the line of the Mont Cenis Tunnel. Traced through Piedmont, they are found to play an important part in the structure of the northern Apennines, where they contain the celebrated statuary marbles of Carrara (p. 629). They have undergone, in these mountainous tracts, extensive metamorphism, the original shales or marls being changed into lustrous schists, and the limestones into crystalline marbles. But even in this altered condition Triassic fossils have been found in them.

Already in Triassic time a notable distinction had been established between the geographical conditions of the regions now marked by the eastern and western Alps. The line of division between the two areas may be said to coincide generally with that ancient line of N.E. and S.W. disturbance known as the "Rhine-Ticino fault." To the west the Triassic deposits point to varying conditions of lagoons and inland seas. Eastward, however, the corresponding deposits attain an enormous development, and are now recognised as presenting a record of the deeper water or pelagic conditions of the Triassic period. As Mojsisovics has remarked, what England and North America are for the Palæozoic formations in general, what Bohemia is for the Silurian system, what the Jura Mountains are for the Jurassic deposits, the eastern Alps are for the Trias.[2] Special interest attaches to the Trias of the eastern Alps from the great thickness of its limestones and their thoroughly marine fauna, with a commingling of Palæozoic and Mesozoic types intercalcated between the Permian and Jurassic systems. It would appear that during the deposition of these limestones the central core of crystalline and Palæozoic rocks of the Alpine chain rose as an island that stretched from the Engadine eastward into Austria. North of this old insular tract the Triassic strata are on the whole somewhat sandy, the accumulation of limestone there having been frequently interrupted by inroads of sand or silt. On the south side the deposition of limestone and dolomite went on more continuously, though interfered with occasionally by submarine volcanic eruptions. Some of the dolomite masses may have been coral-reefs; Mojsisovics even believes that in the conglomeratic portions he can detect traces of the breaker-action by which the reefs were ground down, while the thin marls were deposited in lagoons, or in the inner channels between the reefs and the land. But it is specially deserving of notice that corals were not the only agents in the accumulation of reef-like masses in this region. Alike in the dolomites and the massive limestones calcareous sea-algæ occur so abundantly as to show that they grew up into wide reefs, which, judging from what is known of the distribution of such organisms at present, show that the Triassic sea in these tracts did not exceed 200 fathoms in depth. Though organisms of higher grade are often associated with these reef-building plants, they occur most frequently in the thin-bedded marls and shales at definite horizons in the series of strata.

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[1] See F. von Richthofen, 'Geognostische Beschreibung der Umgegend von Predazzo,' &c. Gotha, 1860; Gumbel, 'Geog. Beschreib. des Bayerisch. Alpen,' 1861; Stur, 'Geologie der Steiermark,' 1871; E. von Mojsisovics, *Jahrb. Geol. Reichsanstalt,* Vienna, 1869, 1874, 1875, 1880; *Abhandl. Geol. Reichsanstalt,* vi. (1875) p. 82; *Verhandl. Geol. Reichsanstalt,* 1866, 1875, 1879; and 'Dolomitriffe Südtirols und Venetiens,' 1878; E. Suss, 'Die Enstehung der Alpen,' 1875; also memoirs by Von Hauer, Laube, Süss, Stache, Stur, Toula, Bittner, and others in the *Jahrb. Geol. Reichsanstalt*; Von Hauer's 'Geologie,' p. 358 *et seq.*; Miss M. Ogilvie, *Quart. Journ. Geol. Soc.* xlix. (1893) p. 1. The fossils are described by Benecke, *Geol. Palæontol. Beitr.* vol. ii.; Mojsisovics, *Abhandl. k. k. Geol. Reichsanst.* vii. x.; Bittner, *op. cit.* vol. xiv.; G. L. Laube, *Denksch. Akad. Wien,* xxiv.-xxx.; numerous other memoirs are cited by Mojsisovics in his 'Dolomitriffe.'

[2] 'Die Dolomitriffe,' p. 39.

Having regard to the lithology and palæontology of the Alpine Trias, Mojsisovics proposed some years ago to regard the system in the eastern Alps as pointing to the existence of two great marine "provinces." The larger of these lay over the sites of North and South Tyrol, Lombardy, and Carinthia, and stretched far to the east. To this area the able Austrian investigator gave the name of the "Mediterranean province." To the other, which occupied a limited tract on the north-east slopes of the Austrian Alps, extending from the Salzkammergut into Hungary, he gave the designation of "Juvavian province" (from the old Roman name of Salzburg). Though the Triassic deposits of these two regions were geologically contemporaneous, they enclose remarkably different assemblages of organic remains, insomuch that the palæontological zones which can be determined in the one have not been found to hold good in the other. In no respect is this independence more strongly shown than in the great contrast presented by the Ammonites of the two areas. The Juvavian province has yielded a Triassic cephalopodous fauna far outrivalling in variety and interest that of any other tract. It was for a long time believed that the cephalopods were quite distinct in the two regions, *Phylloceras, Didymites, Halorites, Tropites, Rhabdoceras*, and *Cochloceras* being regarded as the dominant and distinctive genera of the Juvavian province, while *Lytoceras, Sageceras*, and *Ptychites* were equally characteristic of the Mediterranean province.[1] The progress of research, however, has shown that the so-called Juvavian province can no longer be strictly maintained, for the type of rocks and fossils on which it was based have been found in the midst of the Mediterranean. Nevertheless it remains true that the peculiar lithological and palæontological features, as well as the complicated structure, of the district of the Salzkammergut have up to the present time interposed very great difficulties in the way of the institution of any exact comparison between the Triassic succession in that area and in other parts of the Alpine region. The subjoined table, compiled from the results of the latest researches, shows the contrasted grouping of the Triassic formations on the two sides of the eastern Alps, and their distinction from those of the German inland sea, between which and the Alpine basins there seem to have been only occasional and brief intervals of connection:[2]—

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[1] Mojsisovics has recently modified his previously published opinions regarding the order of the Triassic formations in the Salzkammergut, *Sitzb. Akad. Wien*, 1892, p. 780. The views of this observer, however, regarding the succession of the strata are not everywhere accepted among the geologists of Austria. For a recent critique on this subject see A. Bittner, *Jahrb. k. k. Geol. Reichsanst.* vol. xlii. (1892) p. 387.

[2] In the preparation of my account of the Alpine Trias I have been greatly aided by Miss M. M. Ogilvie, whose intimate acquaintance with this geological system in the eastern Alps is well shown in her paper already cited. The table on next page has been entirely drawn up by her.

				In the Northern Alps.				In the Southern Alps.		
German Trias.[1]		Stages according to Mojsisovics.	Alpine Fossil Zones.	Bavarian and North Tyrol.		Upper and Lower Austria.		Lombardy Alps.	Carinthian Alps and S. Tyrol.	
Rhætic beds.		Rhætic Stage.	1. *Megalodon scutatus* and *Avicula contorta.*	Dachstein Limestone. Kossen beds.	Dachstein and Coral-reef Limestone.	Dachstein Limestone or Kossen beds.	Hallstadt (Salzkammergut) development of limestones, dolomites, &c., with lenticular fossiliferous intercalations.	Kössen beds (Arzzarola beds).	Dachstein Dolomite.	
		Juvavian Stage.	2. *Turbo solitarius* and *Avicula exilis.*	Main Dolomite.		Dachstein Limestone or Dolomite.		Main Dolomite.		
Keuper.	Upper or Gypskeuper. Lower Keuper (Lettenkohle).	Carinthian Stage.	3. *Trachyceras aonoides.*	Raibl beds. { "Ostrea" horizon. "Cardita crenata" horizon.		Opponitz Limestone. Lunz Sandstone.		Raibl beds (Gorno and Dossena beds).	Raibl beds. { Torer beds. Dolomite. Fischschiefer.	Raibl beds.
Muschelkalk.	Upper and Middle Limestones.		4. *Trachyceras aon.*	Wetterstein Limestone.	Wetterstein or Reef Limestone.	Partnach beds.		Esino Limestone.	"Erzführende Dolomit" of Raibl. Cassian beds.	Schlern Dolomite.
		Noric Stage.	5. *Trachyceras Archelaus* and *Halobia Lommeli.*	Partnach beds.						
			6. *Trachyceras Curionii.*			Reifling Limestone.		"Halobia" Shales or Prezzo Limestones.	Wengen beds. Buchenstein beds.	
	Lower Limestones (Wellenkalk).		7. *Ceratites trinodosus.*	Alpine Muschelkalk.		Guttenstein Limestone.		Muschelkalk (Recoaro Limestone).	Muschelkalk (Virgloria Limestone).	Mendola Dolomite.
			8. *Ceratites binodosus* and *Terebratula vulgaris.*							
Bunter.	Roth horizon. Middle and Lower Buntsandstones.		9. *Myophoria costata* and *Tirolites cassianus.*	"Myophoria" beds or Reichenhall Limestone with beds of salt, gypsum, &c. Werfen beds.				Röth Werfen beds.	Werfen beds { Campil beds. Seis beds.	

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[1] For a comparison between the Trias of Germany and that of the Alps, see Wöhrmann, *Jahrb. k. k. Geol. Reichsanst.* 1889, p. 181. A useful summary will be found in Fraas' 'Scenerie der Alpen,' p. 146.

1. **Bunter.**—The base of the Alpine Trias shades down into the Permian formations (Bellerophon limestone, Gröden sandstone), and consists of the group of red sandy micaceous shales known as the Werfen beds (from Werfen in the Salzburg), which form a tolerably persistent horizon. Among the fossils in the upper part are *Naticella costata*, *Turbo rectecostatus*, *Trigonia costata*, *Monotis aurita*, and the ammonites *Tirolites* (*Ceratites*) *cassianus*, *Dalmatinus idrianus*, *D. muchianus*, *Trachyceras Liccanum*, *Norites caprilensis*. Some of these organisms occur so abundantly as to form entire beds. Corals, echinoderms, and brachiopods (except *Lingula*) are absent. In the lower part of the group *Monotis Clarai* is especially abundant. The presence here of *Trigonia costata*, a characteristic form of the German Röth, serves to mark the relation of the Werfen beds to the Triassic series of the German area.

2. **Muschelkalk.**—It is above the position of the Werfen beds that the Alpine Trias begins to manifest great lithological differences, not only in the two provinces on the northern and southern sides of the Alps, but even within the confines of each province. The general character of these differences is expressed in the foregoing table. Yet, with some notable exceptions, the palæontological zones can be distinguished. The lower Muschelkalk of the eastern Alps consists in its inferior portion of sedimentary deposits which are largely argillaceous, while the upper part is composed of limestones and dolomites arranged in lenticular reef-like masses. The lower argillaceous division varies in its palæontological character. Mojsisovics distinguishes three facies, the lowest in which lamellibranchs predominate (Recoaro), and which shows a close lithological and palæontological relation to the German Muschelkalk, followed by one with brachiopods and land-plants, and that by a third with cephalopods (Dont, Val Inferna and Brags). The calcareous group sometimes resembles in lithological character the German Wellenkalk, but in certain places it assumes the aspect of reefs. Among the most important fossils of the Alpine Lower Muschelkalk some are common to this stage in Germany, such as *Spiriferina Mentzeli*, *S. hirsuta*, *Rhynchonella securtata*, *Terebratula vulgaris*, *T. angusta*, *Myophoria vulgaris*, *Pecten discites*, *Encrinus gracilis*, *Ceratites trinodosus*. But there remains a large number of peculiar forms, especially the abundant ammonites (*Ptychites*, *Trachyceras*, numerous species, *Lytoceras*). The Upper Muschelkalk is generally a dark grey to black limestone, but sometimes (Salzkammergut) is red and like a marble. Among the typical fossils are *Daonella Sturi*, *D. parthanensis*, *Orthoceras campanile*, *Nautilus Pichleri*, *Ptychites gibbus*, *Arcestes Bramantei*, *Ægoceras megalodiscus*, *Ceratites* (*Trachyceras*) *trinodosus*, and other genera.

3. **Noric Stage.**—It was at the close of the deposition of the Alpine Muschelkalk and the beginning of the Noric stage that the two great biological provinces above referred to were finally established. The general grouping of the formations in each area and the striking difference they present even within the same area are best understood from the inspection of such a table as that given above. On the southern side of the Alps two groups in this stage have been recognised: (1) the Buchenstein beds, consisting of flaggy and nodular limestones, with hornstone concretions. These strata have not yet been found in the northern Alps. Among their fossils are *Orthoceras Böckhi*, *Arcestes trompianus* and other species, *Ptychites angusto-umbilicatus*, *Sageceras Zsigmondyi*, *Lytoceras*, *cf. wengenense*, *Trachyceras Curionii*, *T. Reitzi* and other species, *Spiriferina Mentzeli*, *Daonella Taramellii*, and other species. (2) The Wengen beds comprise all the strata lying between the Buchenstein beds and the base of the St. Cassian group. Their most important material consists of a dark sandstone with shaly partings, derived chiefly from volcanic detritus. In South Tyrol and in Carinthia sheets of lava and tuff lie at the base of this group, and thicken out round the centres of eruption. With these interbedded igneous rocks are associated bosses and dykes of augite-porphyry and melaphyre. A characteristic feature of the Wengen beds is the great development of reefs formed by calcareous algæ (*Gyroporella*, including *Diplopora*), and built up into enormous masses of limestone and dolomite with corals, large Naticas, and Chemnitzias. Among

the characteristic fossils of the Wengen beds are *Trachyceras Archelaus*, and numerous other species, *Arcestes tridentinus*, *Pinacoceras daonicum*, *Halobia Lommeli*, with in some places remains of land-plants—*Equisetites arenaceus*, *Calamites arenaceus*, *Neuropteris* several species, *Sagenopteris*, *Pecopteris*, *Thinnfeldia*, *Pterophyllum*, *Tæniopteris*, *Voltzia*.

4. Carinthian Stage.—The geographical distribution of the two marine provinces lasted beyond the early part of this stage. The separation between these areas gradually disappeared, and some of their peculiar ammonites began to migrate from the one territory to the other. In the southern area Mojsisovics has noted three distinct Carinthian groups: (1) the St. Cassian beds, consisting of brownish calcareous marls, limestones, and oolites. This group has long been celebrated for the astonishing abundance and variety of its organic remains. The Echinoderms are particularly prominent. Abundant also are the species of *Halobia* (*Daonella*) (*H. cassiana* and *H. Richthofeni*). Corals abound in the neighbourhood of the dolomite-reefs, and the coral banks, like the beds of echinoderms, can be traced laterally into these reefs. The St. Cassian beds are represented in other parts of the Alps by fossiliferous limestones (Marmolata and Esino limestones in South Tyrol and Lombardy, Wetterstein limestone in North Tyrol) and nearly unfossiliferous dolomites (Schlern dolomite in South Tyrol, "Erzfuhrende Dolomit" of Carinthia) of the "reef-type" of Mojsisovics. Out of the large series of fossils the following may be mentioned here:—*Trachyceras aon*, species of *Arcestes*, *Lobites*, *Orthoceras*, *Nautilus*, *Bactrites*, *Gervillia angusta*, *Koninckina Leonardi*, *Rhynchonella semiplecta*, *Encrinus cassianus*, *Pentacrinus propinquus*, *Cidaris dorsata*. (2) The Raibl beds mark the close of the separation of the two provinces, for they range from the one into the other. They consist of dark bituminous marly strata, with lenticular beds and thick reef-like masses of limestone, and frequently with gypsum and rauchwacke. Their fauna, distinguished by the large number of littoral lamellibranchs, includes *Trigonia Kefersteini*, *Cardita Gümbeli*, *Corbula Rosthorni*, *Halobia rugosa*, *Gervillia bipartita*, *Megalodus carinthiacus*, *Chemnitzia eximia*, *Nautilus Wulfeni*, *Trachyceras aonoides*. The Lunz sandstones, which belong to this horizon, have yielded numerous land-plants comprising many species of *Pterophyllum* and forms of *Equisetites*, *Calamites*, *Neuropteris*, *Alethopteris*, &c. (3) The beds comprising the zone of *Avicula exilis* and *Turbo solitarius* show a return of the dolomitic condition of earlier parts of the system. These conditions had already set in during the deposition of the Raibl beds, but they reached their full development during the accumulation of the next group, when masses of dolomite ranging up to nearly 4000 feet in thickness were laid down. This group of rocks, though placed by Mojsisovics in the Carinthian stage, is by other authors considered to be Rhætic. In North Tyrol it is known as the Main Dolomite (Hauptdolomit), in the Salzkammergut as the lower part of the Dachstein limestone, which forms an important feature in the scenery of the district. These rocks everywhere present a great contrast to the strata below them in their poverty of organic remains. Some of their most prominent fossils are casts of *Megalodus* (*M. Gümbeli*, *M. complanatus*, *M. Mojsvári*, &c.), and remains of calcareous algæ (*Gyroporella*). The bituminous Seefeld beds of the North Tyrol have yielded many fishes (*Semionotus*, *Lepidotus*, *Pholidophorus*) and remains of plants.

Until recently, according to Mojsisovics, the order of superposition of the rocks in the Hallstadt area was misinterpreted. He now believes that the Hallstadt marble does not form a continuous mass overlying the Zlambach beds, but that the latter, instead of underlying the Hallstadt rock, actually lie within it. He has grouped a section of the Hallstadt series as a separate stage under the name of "Juvavian." It consists at the base of red and variegated lenticular seams of limestone with *Sagenites Giebeli*. Then follow red lenticular limestones with gasteropods (zone of *Cladiscites ruber*). It is here that the Zlambach beds come in with their *Choristoceras Haueri*. They are succeeded by grey limestone with *Pinacoceras Metternichi*, and this by seams of limestone carrying *Cyrtopleurites bicrenatus*.[1] This whole series, comprising several palæontological zones, is regarded by Mojsisovics as the equivalent in time of the Main Dolomite.

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[1] Mojsisovics, *Sitzb. Akad. Wien*, 1892, p. 769.

5. **Rhætic Stage.**—Two distinct facies of this stage are developed in the eastern Alps, but the unity of the deposits over the whole region is shown by the presence of the characteristic *Avicula contorta*. The Kossen beds are a marly, highly fossiliferous group of strata, marking probably the shallower water, while the upper Dachstein limestone into which they merge may indicate the opener sea. Suss has distinguished a series of "facies" in this group, the lowest (Swabian) marked by the preponderance of lamellibranchs, the next (Carpathian) by the abundance of *Terebratula gregaria* and *Plicatula intusstriata*; the Hauptlithodendron-limestone—a thick mass of coral limestone; the Kossen facies includes the dark brachiopod limestones with shaly partings, while the Salzburg facies is recognised by the prominence of its cephalopods (*Choristoceras Marshi*, *Ægocerus planorboides*).

The Kossen beds are most fully developed in the northern Alps, more particularly in Bavarian and North Tyrol, thinning out towards Salzkammergut, while the dolomitic facies of Dachstein limestone predominates in the southern Alps, the fossiliferous marly facies only appearing in the Lombardy Alps. The occurrence of the fossiliferous Rhætic beds in the Alps gave not only the first clue to the identity in time of the Triassic beds in Alpine and extra-Alpine regions, but it has proved of the greatest importance in tracing the zonal parallelism of the Triassic succession within the Alps themselves. As has been said, a great thickness of wholly unfossiliferous dolomitic and gypsiferous rock sometimes occurs in the western Alps, and it would be impossible to assign a Triassic age to any part of this series were it not for the presence of well-known Rhætic fossils in the beds immediately succeeding them. Again, the same fossils give undoubted evidence of the gradual submersion of the island of older crystalline and Palæozoic rock in the Triassic sea of the eastern Alps. Rhætic fossils are found on the Radstadter Tauer and on the Stubey Mountains in the central chain of the Alps.

The intrusive volcanic rocks of the celebrated districts of Predazzo and Monzoni in South Tyrol are referred by some authors to Lower, by others to Upper Triassic time. At Predazzo there is a core of orthoclase porphyry and tourmaline granite with an envelope of syenite, by which, among the now familiar phenomena of contact-metamorphism, the Triassic limestones have been in places converted into marble. Similar phenomena are presented at Monzoni, where a central boss of augite-syenite, traversed by veins of gabbro, melaphyre, &c., cuts across the Triassic strata (*ante*, p. 604).

The Triassic rocks of the Alps have participated in the great earth-movements to which this chain of mountains owes its structure, and they consequently present remarkable cases of dislocation, inversion, and even of metamorphism. Thus the Triassic formations of the Radstadter Tauer in the Tyrol cannot be separated from the calc-mica schist of that district, and Professor Suss regards this schist as an altered Triassic limestone.[1]

Spitzbergen.—Since the Alpine type of the Trias has been recognised as that of the open sea, it has been traced far and wide over the Old World, northwards into the Arctic circle, eastwards across Asia to Australasia, and along the eastern borders of the Pacific Ocean. In northern Siberia, at the mouth of the River Olenek, and in Spitzbergen, Triassic strata have been found with a characteristic marine fauna, including the following genera of cephalopods: *Dinarites*, *Ceratites*, *Sibirites*, *Prosphingites*, *Popanoceras*, *Monophyllites*, *Xenodiscus*, *Meekoceras*, *Hungarites*, *Ptychites*, *Pleuronautilus*, *Nautilus*, and *Atractites*; also species of *Pseudomonotis*, *Oxytoma*, *Avicula*, *Pecten*, *Gervillia*, *Cardita*, *Lingula*, *Spiriferina*, and *Rhynchonella*, together with remains of fish and reptiles (*Acrodus spitzbergensis*, *Ichthyosaurus polaris*, *I. Nordenskiöldii*).[2]

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[1] *Anzeiger Akad. Wien*, No. xxiv. 20th Nov. 1890.

[2] A. E. Nordenskiöld, *Geol. Mag.* 1876, p. 741; A. Bittner and A. Teller, *Mém. Acad. St. Pétersbourg*, vol. xxxiii.; Mojsisovics, *Verhandl. k. k. Geol. Reichsanst.* 1886, No. 7.

Asia.—The Trias has a wide extension in this continent. In the old district of Mysia. Asia Minor, dark shales and limestones enclose undoubted Triassic forms such as *Arcestes*, *Nautilus*, and *Halobia*.[1] Strata with *Ceratites* and *Orthoceras* occur in Beloochistan, and in the Salt Range of the Punjab. In northern Kashmir and western Tibet a well-developed succession of Triassic formations appears among the Himalayan ranges, sometimes exceeding 4000 feet in thickness. It contains many of the same species of fossils as occur in the Alpine Trias. Some of its forms are *Ammonites floridus*, *A. diffusus Halobia Lommeli*, *Monotis salinaria*, *Megalodus triqueter*. The researches of Mr Griesbach have added much to our materials for a comparison between these Himalayan Triassic rocks and their representatives in Europe. At the base of these formations in the Himalayan regions lies a group of strata, the *Otoceras* beds, with a cephalopodan fauna poor in species but rich in individuals (*Xenodiscus*, *Meekoceras*, *Otoceras*, *Prosphingites*). These are followed by another lower Trias member, with a large assemblage of cephalopods resembling that of the Ceratite beds of the Salt Range, which are regarded by Waagen as homotaxial with the Bunter sandstone of Europe. The horizon of the Muschelkalk is represented by rocks in which there is a blending of the palæontological characters of the Arctic and Mediterranean types of this formation. Three upper Triassic groups have been recognised. Of these the lowest,' consisting of black Daonella limestone, contains forms of *Arcestes*, *Entomoceras*, and *Arpadites*, the middle contains small ammonites of the genera *Sibirites*, *Heraclites*, and *Halorites*, while the highest group may be compared with the zone of *Tropites subbullatus*, at the base of the Carinthian stage of the eastern Alps.[2] The freshwater Karharbári beds, near the base of the Gondwána series of peninsular India, contain a Bunter assemblage of plants, including *Voltzia heterophylla* and *Albertia* (near *A. speciosa*);[3] also several cycads (*Glossozamites*, *Zamia*) and a number of ferns (*Neuropteris*, *Gangamopteris*, *Glossopteris*, *Sagenopteris*). It has been already observed that some of these types, which were believed to be exclusively Mesozoic, occur in Australia associated with a Carboniferous Limestone fauna (*ante*, p. 839). The Tálchir group contains boulder-beds that may indicate glacial action in Triassic or Permian time. The Damuda group, which comprises nearly all the coal-fields of the Indian peninsula, contains a remarkable flora, distinguished by the abundance of ferns (*Glossopteris*, *Gangamopteris*, *Sagenopteris*, *Tæniopteris*, &c.), and by its mingled Palæozoic and Mesozoic characters. The Panchet group, crowning the lower Gondwána system, is composed of sandstones with bands of red clay, the whole having a thickness of 1800 feet, and yielding the Rhætic ferns *Pecopteris concinna* and *Cyclopteris pachyrhachis*, the Triassic and Rhætic genus of horse-tail *Schizoneura*; the labyrinthodonts *Gonioglyptus* and *Pachygonia*, allied to Triassic forms, together with *Dicynodon*, *Epicampodon*, &c.[4]

Australia.—In New South Wales a group of yellowish-white sandstones (Hawkesbury beds) about 1000 feet thick lies unconformably upon the coal-bearing strata referred to the Permian period. This group forms the picturesque cliffs around the coast of Port Jackson, and has furnished the building-stone for the principal public buildings in Sydney. It has yielded a large number of plants (*Phyllotheca*, *Sphenopteris*, *Neuropteris*, *Thinnfeldia*—common, *Odontopteris*, *Alethopteris*, *Macrotæniopteris*, *Podozamites*, and *Walchia*); also the fishes *Palæoniscus antipodeus*, *Myriolepis Clarkei*, *Cleithrolepis granulatus*, and labyrinthodonts, but no marine shells. At Gosford, near the base of the Hawkesbury beds, in a thin seam of grey shale, a large collection of fishes has been obtained. The animals seem to have lived in some land-locked lake or estuary, and to have been killed in large numbers by the sudden silting up of the water with coarse sand and gravel. They belong to at least six genera, four of which occur in the European Trias. Of these four, two (*Dictyopyge* and *Semionotus*) are typically Triassic, while the third (*Belonorhynchus*) commonly ranges to the Lias, and the fourth (*Pholidophorus*) is best developed in the Jurassic system. The fifth genus (*Pristisomus*) is new, but scarcely higher in rank than *Semionotus*, while the sixth (*Cleithrolepis*) has only been definitely recognised in the Stromberg beds of South Africa, the age of which may be Triassic or Lower Jurassic.[1] On the Hawkesbury sandstones, perhaps unconformably, lies a group of shales (Wianamatta beds) with abundant plants, chiefly ferns, sometimes aggregated into thin seams of coal (*Thinnfeldia*, *Odontopteris*, *Pecopteris*, *Macrotæniopteris*, *Phyllotheca*, and *Unio* and *Unionella*). These two groups of strata are with some hesitation referable to the Trias.[2]

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[1] Neumayr, *Sitzb. Akad. Wien*, 1887.

[2] Mojsisovics, *Sitzb. Akad. Wien*, ci. (1892) p. 372.

[3] Medlicott and Blanford's 'Geology of India,' pp. xlvi. 114. C. L. Griesbach, *Mem. Geol. Surv. India*, vol. xxiii.

[4] 'Geology of India,' p. 131.

New Zealand.—Under the name of Trias, Sir J. Hector groups a great thickness of strata divisible into three series. (1) The Oreti series—a thick mass of green and grey tuff-like sandstones and breccias, with a remarkable conglomerate (50 to 400 feet thick) containing boulders of crystalline rocks sometimes 5 feet in diameter, found both in the North and South Islands; fossils, chiefly Permian and Triassic, but with a *Pentacrinus* like a Jurassic species. (2) Above these beds lies the Wairoa series, containing *Monotis salinaria*, *Halobia Lommeli*, &c., and also plants, as *Dammara*, *Glossopteris*, *Zamites*, &c. (3) The Otapiri series, which, from the commingling of fossils nearly allied to Jurassic species with others which are Triassic and some even Permian, and from the presence of many forms identical with those of the Rhætic formations of the Alps, is assigned to the Upper Trias or Rhætic division.[3]

Africa.—In South Africa the "Karoo beds" spread over a wide area of country, consisting of nearly horizontal incoherent sandy materials, from which the remarkable assemblage of amphibian and reptilian remains already referred to has been obtained. The similarity of the fossils in these rocks and in those which are assigned to the Triassic series in India and Australia deserves to be specially remarked.

North America.—Rocks which are regarded as equivalent to the European Trias cover a large area in North America. On the Atlantic coast, they are found in Prince Edward's Island, New Brunswick, and Nova Scotia; in Connecticut, New York, Pennsylvania, and North Carolina; in Honduras and along the chain of the Andes into Brazil and the Argentine Republic. Spreading also over an enormous extent of the western territories, they cross the Rocky Mountains into California and British Columbia. They consist mainly of red sandstones, passing sometimes into conglomerates, and often including shales and impure limestones. But an important distinction may be drawn between the system as developed in the eastern and central parts of the continent, on the one hand, and along the Pacific slope on the other. In the former wide region, the rocks, evidently laid down in inland basins, like those of the same period in central Europe, are remarkably barren of organic remains. Their fossil contents include remains of terrestrial vegetation, with footprints and other traces of reptilian life, but with hardly any indications of the presence of the sea. This is the German type of the system.

The fossil plants of the Triassic rocks in the valley of the Connecticut and New Jersey present a general facies like that of the European Triassic flora. Among them are horse-tails (*Equisetum*, *Schizoneura*), cycads (*Pterophyllum* (some European species), *Zamites*, *Otozamites*, *Sphenozamites*, *Nilssonia polymorpha*, *Dioonites*), ferns (*Pecopteris*,

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[1] A. S. Woodward, *Mem. Geol. Surv. N.S. Wales*, *Palæontology*, No. 4 (1890), p. 54.

[2] C. S. Wilkinson, 'Notes on Geology of New South Wales,' Sydney, 1882, p. 53. O. Feistmantel, *Mem. Geol. Surv. N.S. Wales*, *Palæontology*, No. 3 (1890); R. Etheridge jun. *op. cit.* No. 1 (1888).

[3] 'Handbook of New Zealand,' p. 33. F. W. Hutton, *Quart. Journ. Geol. Soc.* (1885) p. 202.

Neuropteris, *Tæniopteris*, *Clathropteris*) and conifers (*Cheirolepis*).[1] In Virginia, where two distinct Mesozoic floras have been preserved, the older appears to be not more ancient than the Rhætic stage. So abundant is the vegetable matter in the sandy strata of the series as to form seams of workable coal, one of which is sometimes 26 feet thick. The plants include species of *Equisetum*, *Schizoneura*, *Macrotæniopteris*, *Acrostichites*, *Cladophlebis*, *Lonchopteris*, *Clathropteris*, *Pterophyllum*, *Ctenophyllum*, *Podozamites*, *Cycadites*, *Zamiostrobus*, *Baiera*, *Cheirolepis*, &c. Again in North Carolina a coal-bearing formation occurs with a similar flora, 41 per cent of the plants being also found in Virginia.[2]

The fauna of the North American Triassic rocks is remarkable chiefly for the number and variety of its vertebrates. The labyrinthodonts are represented by footprints, from which upwards of fifty species have been described. Saurian footprints have likewise been recognised; in a few cases their bones also have been found. Some of the vertebrates had bird-like characteristics, among others that of three-toed hind feet, which produced impressions exactly like those of birds (p. 864). But, as already remarked, it is by no means certain that what have been described as "ornithichnites" were not really made by deinosaurs. The small insectivorous marsupial (*Dromatherium*) above referred to, found in the Trias of North Carolina, is the oldest American mammal yet known.

On the Pacific slope, however, a very different development of the Trias occurs. The Alpine or pelagic type of the system is here seen. The strata are estimated to attain a thickness of sometimes as much as 14,000 or 15,000 feet. Like the Alpine formations, they include a mingling of such Palæozoic genera as *Spirifer*, *Orthoceras*, and *Goniatites*, with characteristically Secondary forms as ammonites (*Ceratites Haidingeri*, *Ammonites ausseanus*, &c.) and bivalves of the genera *Halobia*, *Monotis*, *Myophoria*, &c.

Section ii. Jurassic.

This great series of fossiliferous rocks, first recognised by William Smith in the geological series in England, received originally the name of "Oolitic" from the frequent and characteristic oolitic structures of many of its limestones. Lithological names being, however, objectionable, the term "Jurassic," applied by the geologists of France and Switzerland to the great development of the rocks among the Jura Mountains, has now been universally adopted to embrace both Lias and Oolites.

§ 1. General Characters.

Jurassic rocks have been recognised over a large part of the world. But they do not present that general uniformity of lithological character so marked among the Palæozoic systems. The suite of rocks changes as it passes from England across France, and is replaced by a distinctly different type in Northern Germany, and by another in the Alps. If we trace the system farther into the Old World we find it presenting still another aspect in north-western India, while in America the meagre representatives of the European development have again a facies of their own. Hence no generally applicable petrographical characters can be assigned to this part of the geological record.

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[1] J. S. Newberry, *Monographs of U.S. Geol. Survey*, vol. xiv. (1888) and *Amer. Journ. Sci.* xxxvi. (1888) p. 342.

[2] W. M. Fontaine, *Monogr. U.S. Geol. Surv.* vol. vi. (1883). The younger Mesozoic flora of Virginia is probably Neocomian (*postea*, p. 923).

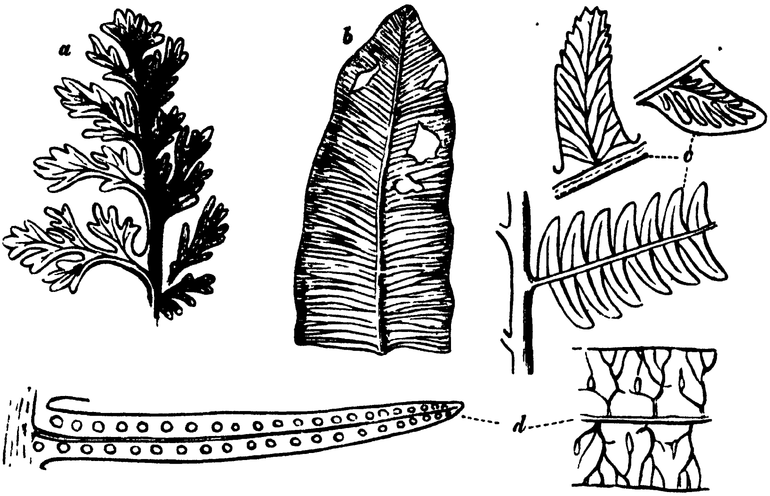

Fig. 381.—Jurassic Ferns (Lower Oolite).

a, Sphenopteris trichomanoides, Brongn.; *b*, Tæniopteris major, Lindl. and Hutt. (¾); *c*, Pecopteris dentata, Lindl. and Hutt. (nat. size and mag.); *d*, Phlebopteris polypodioides, Brongn. (nat. size and mag.)

The flora of the Jurassic period, so far as known to us, was essentially gymnospermous.[1] The Palæozoic forms of vegetation traceable up to the close of the Permian system are here absent. Equisetums, so common in the Trias, are still abundant, one of them (*E. arenaceum*) attaining gigantic proportions. Ferns likewise continue plentiful, some of the chief genera being *Alethopteris*, *Sphenopteris*, *Phlebopteris*, *Oleandridium*, and *Tæniopteris* (Figs. 381, 382). The cycads (Fig. 383), however, are the dominant forms, in species of *Zamites*, *Pterophyllum*, *Anomozamites*, *Nilssonia* (*Pterozamites*), *Dioonites*, *Podozamites*, *Sphenozamites*, *Glossozamites*, *Otozamites*, *Cycadites*, *Bucklandia* (*Clathraria*), *Bennettites*, *Mantellia* (*Cycadites* and *Cycadoidea*), *Zamiostrobus* (*Cycadeostrobus*), *Beania*, *Cycadospadix*, *Cycadinocarpus*. *Williamsonia* is by some botanists placed with the cycads, by others with the dicotyledons or with the monocotyledons. Conifers also

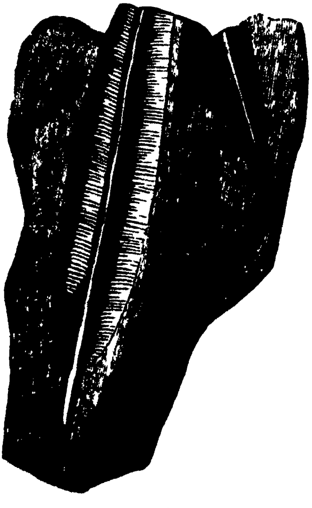

Fig. 382.—Jurassic Fern—Tæniopteris vittata, Brongn. (½).

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[1] The entire known Jurassic flora of Britain, up to the top of the Portlandian stage,

are found in some numbers, particularly Araucarians of the genera *Pachyphyllum* (*Walchia*) and *Araucaria*; also *Pinites*, *Peuce*, *Brachyphyllum*, and *Thuyites*. This flora appears to have flourished luxuriantly even as far north as Spitzbergen, where the large number of cycads gives an almost tropical aspect to the Jurassic vegetation of this Arctic island.[1]

The Jurassic fauna[2] presents a far more varied aspect than that of any of the preceding systems. Owing to the intercalation of fresh-water, and sometimes even terrestrial, deposits among the marine formations, traces of the life of the lakes and rivers, as well as of the land itself, have been to some extent embalmed, besides the preponderant marine forms. The conditions of sedimentation have likewise been favourable for the preservation of a succession of varied phases of marine life. Professor Phillips directed attention to the remarkable ternary arrangement of the English Jurassic series.[3] Argillaceous sediments are there succeeded by arenaceous, and these by calcareous, after which the argillaceous once more recur. These changes are more or less local in their occurrence, but five repetitions of the succession are to be traced from the top of the Lias to the top of the Portlandian stage. Such an alternation of sediments points to interrupted depression of the sea-bottom.[4] It permitted the growth and preservation of different kinds of

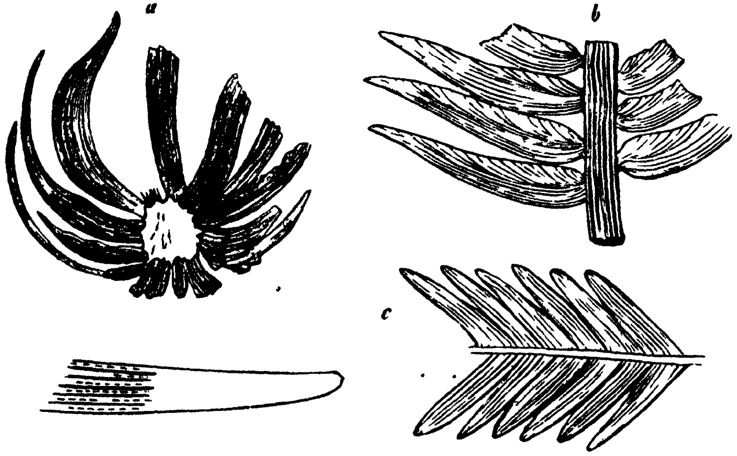

Fig 883.– Jurassic Cycads (Lower Oolites)
a, Williamsonia (Zamia) gigas, Carr (¼), *b*, Otozamites lanceolatus, Lindl and Hutt. (¼), *c*, Williamsonia hastula, Bean (nat size and mag)

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comprises between 60 and 70 genera and about 200 species—doubtless a mere fragment of the whole flora of the period.

[1] O. Heer, *K. Svensk. Vet. Akad. Handl.* xiv. No 5, p. 1.

[2] The total Jurassic fauna of Britain up to the top of the Portlandian stage was estimated in 1882 to include 450 genera and 4297 species, which is likewise but a small proportion of the whole original fauna. Etheridge, *Q. J. Geol. Soc.* 1882, Address.

[3] 'Geology of Oxfordshire,' &c. p. 393.

[4] *Ante*, p. 521.

marine organisms in succession over the same areas,—at one time sand-banks, followed by a growth of corals, with abundant sea-urchins and shells, and then by an inroad of fine mud, which destroyed the corals, but in which, as it sank to the bottom, the abundant cephalopods and other mollusks of the time were admirably preserved.

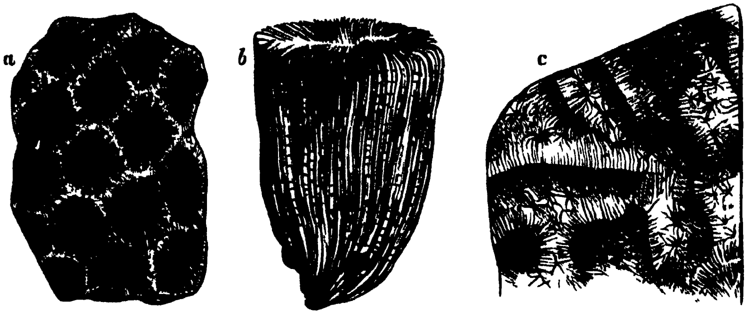

Fig. 384.—Jurassic Corals (Middle Oolite).
a, Isastræa helianthoides, Goldf. ; *b*, Montlivaltia dispar, Phill. ; *c*, Comoseris irradians, M. Edw.

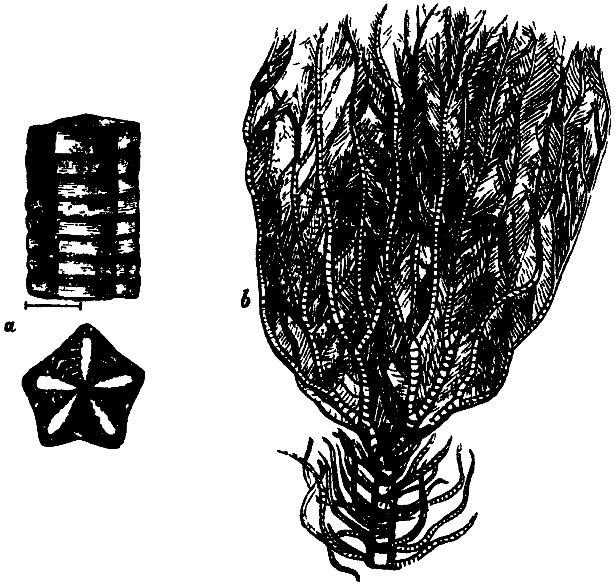

Fig. 385.—Lias Crinoids.
a, Pentacrinus basaltiformis, Goldf. (side view and end view of part of stem);
b, Extracrinus briareus, Mill. (½).

A characteristic feature of the Jurassic fauna is the abundance of its beds or banks of coral. During the time of the Corallian formation, in particular, the greater part of Europe appears to have been submerged beneath a coral sea. Stretching through England from Dorsetshire to Yorkshire, these coral accumulations have been traced across the Continent from Normandy to the Mediterranean, over the east of France, through the whole length of the Jura Mountains, and along the flank of the Swabian Alps. The corals belonged to the genera *Isastræa*, *Thamnastræa*, *Thecosmilia*, *Calamophyllia*, *Montlivaltia*, &c. (Fig. 384). In the Jurassic seas generally echinoderms were abundant, particularly crinoids of the genera *Pentacrinus*, *Extracrinus* (Fig. 385), and *Apiocrinus*. Among these the multiplication of identical or nearly identical parts reaches a climax in the *Extracrinus briareus*, which is estimated to have possessed no fewer than 600,000 distinct ossicles. There were likewise several forms of star-fishes, but it is in the great profusion of echinoids that the echinoderms now begin to be distinguished. Among these the genera *Acrosalenia*, *Cidaris* (Fig. 386), *Hemicidaris*, *Echinobrissus*, *Hemipedina*, *Pseudodiadema*, *Clypeus*, *Pygaster*, and *Pygurus* were conspicuous. Polyzoa of creeping, foliaceous and dendroid types abound on many horizons in the Jurassic system. They include some extinct forms, but also some (*Diastopora*, *Alecto*) which have survived to the present time. They occur plentifully in the Pea-grit beds of the Inferior Oolite near Cheltenham, and Forest Marble near Bath, and still more abundantly near Metz and near Caen.[1] The brachiopods continue to decrease in importance compared to the prominence they enjoyed in Palæozoic time. So far as known, they are chiefly species of *Rhynchonella* and *Terebratula* (Fig. 387). The last of the ancient group of *Spirifers* (*Spiriferina*) and of the genus *Leptæna* (*Koninckella*, Fig. 388) disappear in the Lias, while *Waldheimia*, a still living genus, now takes its place. Among the lamellibranchs (Figs. 389-392) some of the more abundant genera are *Avicula*, *Pseudomonotis*, *Aucella*, *Posidonomya*, *Gervillia*, *Ostrea*, *Gryphæa*, *Exogyra*, *Lima*, *Pecten*, *Pinna*, *Astarte*, *Cardinia*, *Cardium*, *Gresslya*, *Hippopodium*, *Modiola*,

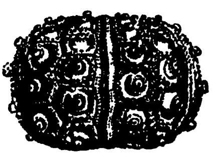

Fig. 386.—Jurassic Urchin. Cidaris florigemma, Phill. (½) Corallian.

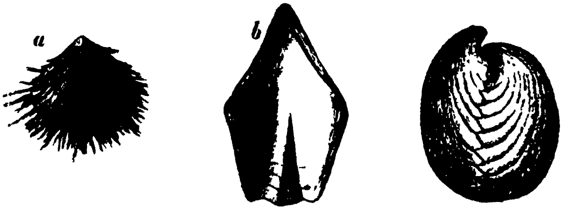

Fig. 387.—Oolitic Brachiopods.
a, Rhynchonella spinosa, Schloth. (½), Lower Oolite ; *b*, Terebratula Phillipsii, Mor. (½), Lower Oolite ; *c*, Rhynchonella pinguis, Rœm. Middle Oolite.

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[1] F. D. Longe, *Geol. Mag.* 1881, p. 23. The genus *Alecto* seems to range back to Lower Silurian times.

Myacites, *Cyprina*, *Isocardia*, *Pholadomya*, *Goniomya*, and *Trigonia*. Some of these genera, particularly the tribe of oysters, are specially characteristic: *Gryphæa*, for example, occurring in such numbers in some of the Lias limestones as to suggest for these strata the name of "Gryphite Limestone," and again in the so-called "Gryphite Grit" of the Inferior Oolite. Different species of *Trigonia*,[1] a genus now restricted to the Australian seas, are likewise distinctive of horizons in the middle and upper part of the system. Many of the most abundant gasteropods (Fig. 393) belong to still living genera, as *Pleurotomaria*, *Cerithium*, and *Natica*. But the most important element in the molluscan fauna was undoubtedly supplied by the cephalopods. In particular, the tetrabranchiate tribe of Ammonites attained an extraordinary exuberance, both in number of individuals and in variety of form (see Figs. 405-409). These organisms possess a great importance to the geologist, for their limited vertical range makes them extremely valuable in marking successive life-zones. The whole Jurassic system has been divided into a series of platforms, each characterised by some predominant species or group of Ammonites. The ammonoid families which had previously existed seem to have in great measure died out, and a new and still richer series took their place at the close of the Triassic period. The old comprehensive genus *Ammonites* has now been broken up into many families and genera. In the older part of the Jurassic system the genera *Arietites*, *Ægoceras*, *Amaltheus*, *Lytoceras*, *Phylloceras*, and *Stephanoceras* are characteristic. Higher up, besides some of these genera, we find *Cosmoceras*, *Harpoceras*, and *Aspidoceras*, and in the upper parts *Perisphinctes* and *Oppellia*. The dibranchiate division was likewise represented by species of cuttle-fish (*Teudopsis*, *Beloteuthis*, *Sepia*, but particularly *Belemnites*, Fig. 394). The Belemnites are the preponderating type, and like the Ammonites, though in a less degree, their specific forms serve to mark life-zones.

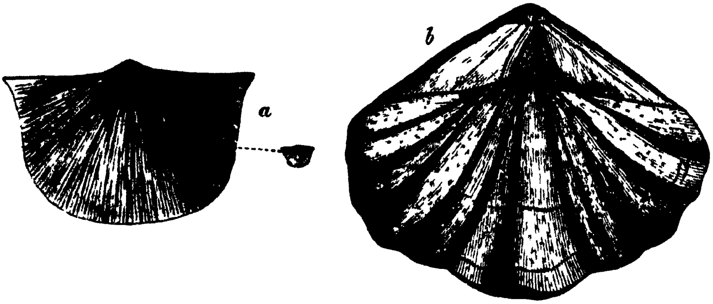

Fig. 388.—Lias Brachiopods.
a, Leptæna (Koninckella) Moorei, Dav. (nat. size and enlarged); *b*, Spiriferina Walcotti, Sby.

No contrast can be more marked than between the crustacean fauna of the Jurassic and that of the older systems. The ancient trilobites and eurypterids, as remarked by Phillips, are here replaced by tribes of long-tailed ten-footed lobsters and prawns, and of representatives of our modern crabs (*Æger*, *Eryon*).[1]

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[1] This genus affords an instructive example of the remarkable changes of form which some genera of shells have undergone. See Lycett's monograph on Trigonia, *Palæontograph. Soc.*

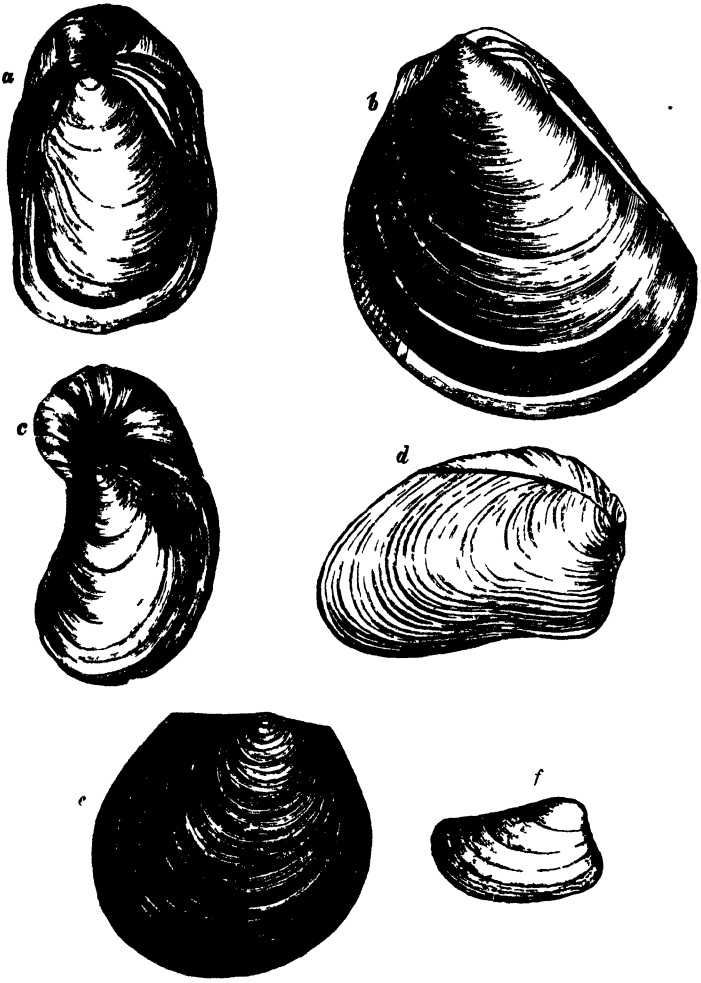

Fig 889 Liassic Lamellibranchs

a, Gryphæa cymbium, Lam (⅓), b, Lima gigantea, Sby (⅓), c, Gryphæa arcuata, Lam (incurva Sby ⅔), d, Hippopodium ponderosum, Sby (¼) e, Posidonomya Bronnii, Goldf nat size), f, Nucula Hammeri, Defr

Here and there, particularly in the Jurassic series of England and

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[1] For an account of the Jurassic decapods of North Germany see G. Krause, *Zeitsch. Deutsch. Geol. Ges.* 1891, p. 171.

Switzerland, thin bands occur containing the remains of terrestrial insects (Fig. 395). The neuropterous forms predominate, including remains of dragon-flies and mayflies. There are also cockroaches and grasshoppers. The elytra and other remains of numerous beetles have been obtained belonging to still familiar types (*Curculionidæ*, *Elateridæ*, *Melolonthidæ*). A wing (*Palæontina oolitica*) disinterred from the Stonesfield Slate was originally believed to be the oldest known trace of a butterfly, but it is now considered to belong to the hemiptera. A few dipterous insects have been detected even as low down as the Lias towards the base of the system.[1]

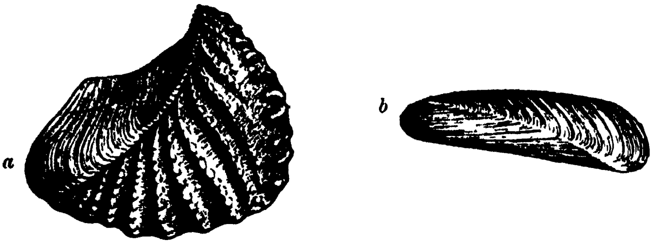

Fig. 390.—Lower Oolitic Lamellibranchs.
a, Trigonia navis, Lam. (⅓); *b*, Modiola (Mytilus) sowerbyana, D'Orb. (½).

In no department of the animal kingdom was the advent of Mesozoic time more marked than among the fishes. The Palæozoic types, with their heterocercal tails, nearly died out. The sharks and rays were well represented by species of *Acrodus* and *Hybodus*, while the ganoids appeared in numerous, mostly homocercal genera, such as *Dapedius*, *Æchmodus*, *Mesodon*, *Gyrodus*, *Lepidotus*, *Pholidophorus*, *Pachychormus*, *Caturus*, *Leptolepis*, *Megalurus*.[2]

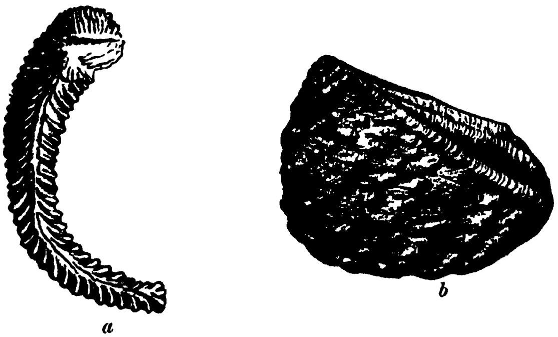

Fig. 391.—Middle Oolitic Lamellibranchs.
a, Ostrea hastellata, Schloth. (½); *b*, Trigonia clavellata, Sby. (½).

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[1] A. G. Butler, *Geol. Mag.* x. (1873) p. 2; i. 2nd ser. (1874) p. 446. Scudder, *Bull. U.S. Geol. Surv.* No. 71 (1891), p. 175, and authorities there cited.

[2] For a list of Liassic fishes, see memoir by H. E. Sauvage, *Ann. Sciences Géol.* vi. (1875).

The most impressive feature in the life of the Jurassic period was the abundance and variety of the reptilian forms. Mesozoic time, as already remarked, has been termed the "Age of Reptiles," and it was especially during the Jurassic period that the maximum development of reptilian types, with the final disappearance of the ancient order of labyrinthodonts and the rise and growth of new orders of reptiles which have long since been extinct, was reached. The first true turtles seem to have made their appearance during this period. Numerous fragments of lacertilians have been obtained. The bones of various crocodilian genera occur, such as *Teleosaurus*, *Steneosaurus*, *Mystriosaurus*, and *Goniopholis*. *Teleosaurus*, found in the Yorkshire Lias and the Stonesfield Slate, was a true carnivorous crocodile, measuring about 18 feet in length, and is judged by Phillips to have been in the habit of venturing more freely to sea than the gavial of the Ganges or the crocodile of the Nile. Of

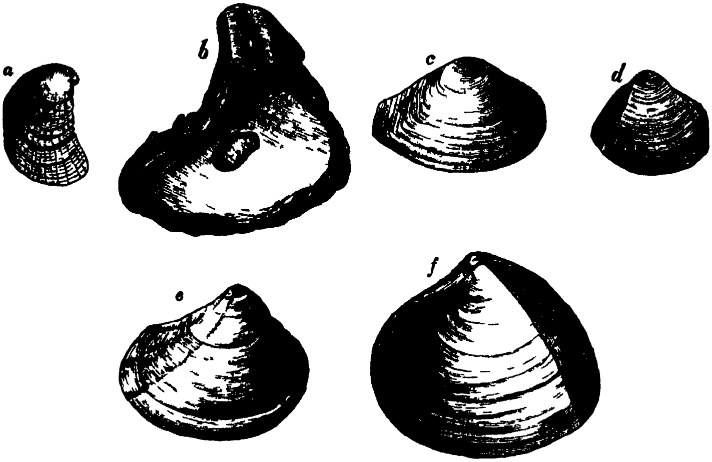

Fig. 392.—Upper Oolitic Lamellibranchs.
a, Exogyra (Ostrea) virgula, D'Orb.; *b*, Ostrea deltoidea, Sby. (¼); *c*, Astarte hartwellensis, Sby. (⅓); *d*, Cardium striatulum, Sby. (½); *e*, Trigonia gibbosa, Sby. (½); *f*, Cardium dissimile, Sby. (¼).

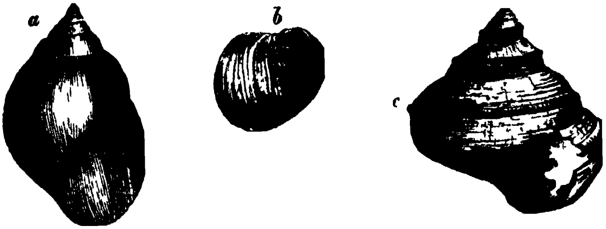

Fig. 393.—Jurassic Gasteropods.
a, Natica hulliana, Lyc. (Lower Oolite); *b*, Nerita costulata, Desh. (Lower Oolite, nat. size and mag.); *c*, Pleurotomaria reticulata, Sow. (Kimeridge clay, ½).

the long-extinct reptilian types, one of the most remarkable was that of the enaliosaurs or sea-lizards. One of these, the *Ichthyosaurus* (Fig. 396, *a*), was a creature with a fish-like body, two pairs of strong swimming paddles, probably a vertical tail-fin, and a head joined to the body without any distinct neck, but furnished with two large eyes, having a ring of bony plates round the eyeball, and with teeth that had no distinct sockets. Some of the skeletons of this creature exceed 24 feet in length. Contemporaneous with it was the *Plesiosaurus* (Fig. 396, *b*),

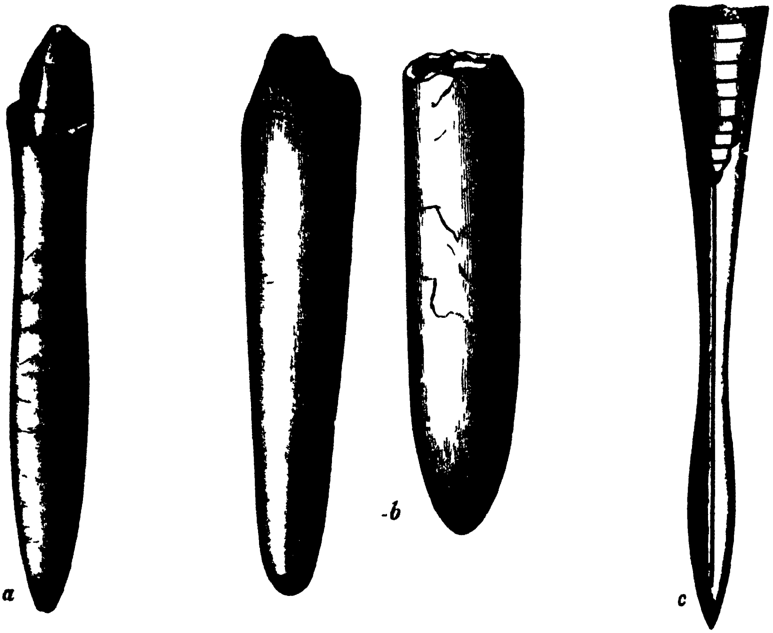

Fig 394.—Jurassic Belemnites
a, Belemnites paxillosus, Schloth (Lias, ½), *b*, B. irregularis, Schloth. (Lias and Lower Oolite, nat. size), *c*, B hastatus, Blainv. (Middle Oolite, ½).

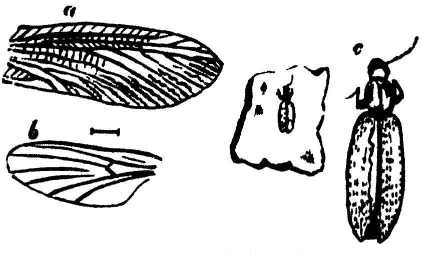

Fig. 395.—Insects, Purbeck Beds.
a, *b*, Wings of Neuropterous Insects (*Corydalis*) (nat. size and mag.); *c*, *Carabus elongatus* (nat. size and mag. Brodie, 'Foss. Insects,' pl. ii. and v.)

distinguished by its long neck, the larger size of its paddles, the smaller

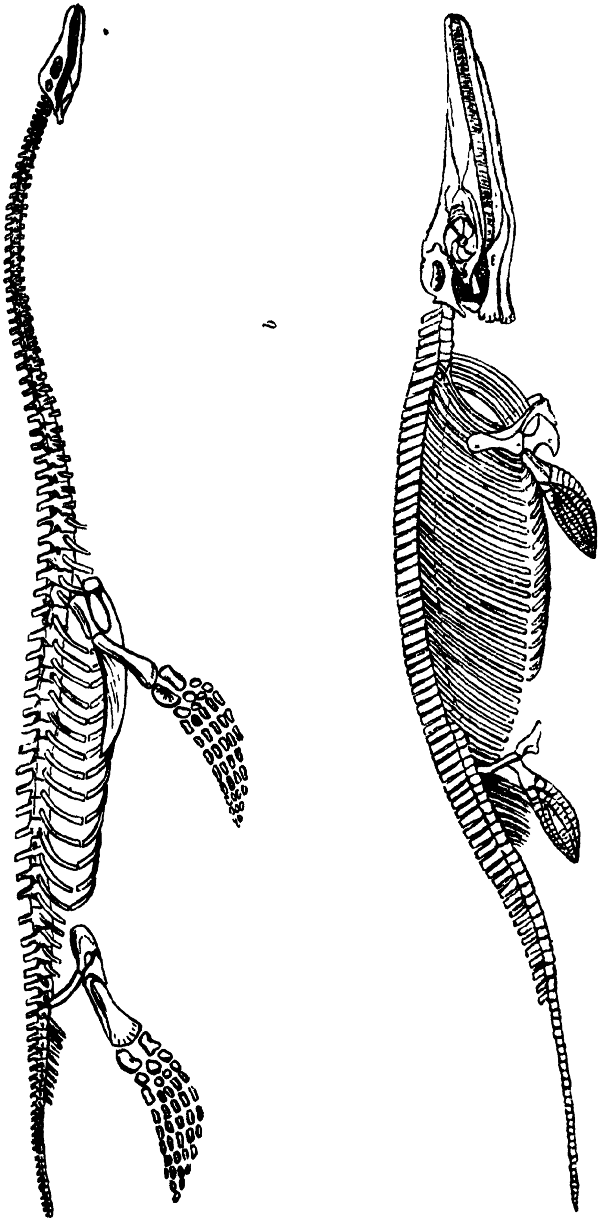

Fig. 396.—Jurassic Enaliosaurs or Sea-lizards.
a, Ichthyosaurus communis, Conyb. (restored by Conybeare and Cuvier); *b*, Plesiosaurus dolichodeirus, Conyb. (restored by Conybeare).

size of its head, and the insertion of its teeth in special sockets, as

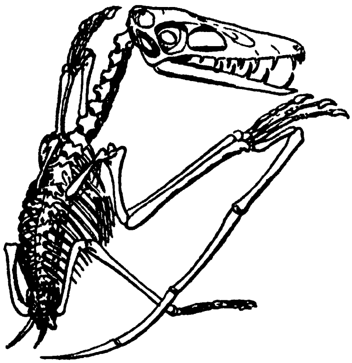

Fig. 397.—Jurassic Pterosaur.
gnathus (Pterodactylus) crassirostris, Goldf. (Middle Oolite).

in the higher saurians. These creatures seem to have haunted the shallow Liassic seas, and, varying in species with the ages, to have survived till towards the close of Mesozoic time.[1] The genus *Pliosaurus*, related to the last-named, was distinguishable from it by the shortness of its neck and the proportionately large size of its head. Another extraordinary reptilian type was that of the pterosaurians or flying reptiles, which were likewise peculiar to Mesozoic time. These huge, winged, bat-like creatures had large heads, teeth in distinct sockets, eyes like the *Ichthyosaurus*, one finger of each fore-foot prolonged to a great length, for the purpose of supporting a membrane for flight, and bones, like those of birds, hollow and air-filled.[2] The best-known genus, *Pterodactylus* (*Scaphognathus*,

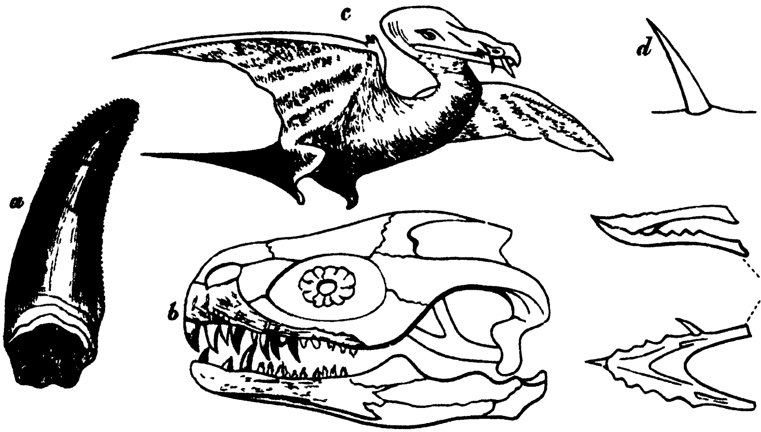

Fig. 398.—Jurassic Deinosaur and Pterosaur.
a, Megalosaurus Bucklandi (Meyer), tooth (½); *b*, Megalosaurus, restoration of head, after Owen ($\frac{1}{10}$); *c*, Rhamphocephalus Bucklandi (Goldf.), restoration, after Phillips (compare Fig. 401); *d*, Do. tooth (nat. size); *e*, Do. jaw (½).

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[1] On the distribution of the Plesiosaurs see a table by G. F. Whidborne, *Q. J. Geol. Soc.* 1881, p. 480.

[2] See Marsh on wings of Pterodactyles, *Amer. Journ. Sci.* April 1882. The remarkable specimen of *Rhamphorhynchus* (*R. Münsteri*) from the Solenhofen Slate, described by this author (Figs. 399, 400, 401), possessed a long tail, the last sixteen short vertebræ of which supported a peculiar caudal membrane which, kept in an upright position by flexible spines, must have been an efficient instrument for steering the flight of the creature. I am indebted to the kindness of Prof. Marsh for the three figures which illustrate this structure.

Fig. 397), had a short tail and jaws furnished from end to end with long teeth. Others were *Dimorphodon*, distinguished especially by long anterior and short hinder teeth, and by the length of its tail, and *Rhamphorhynchus* (Figs. 398, 399, 400, 401), also possessing a long tail, with a caudal membrane and having formidable jaws, which may have terminated in a horny beak. These strange harpy-like creatures were able to fly, to shuffle on land, or perch on rocks, perhaps even to dive in search of their prey. The long slender teeth which some of them possessed probably indicate that the creatures lived on fish. Lastly, the

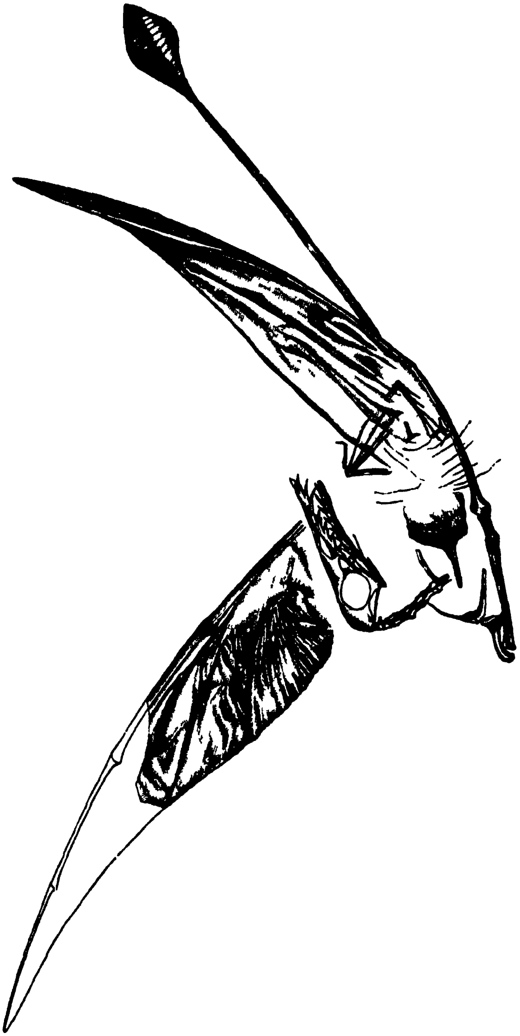

Fig. 399.—Jurassic Pterosaur.

Rhamphorhynchus Munsteri, Goldf. (¼). The animal lies upon its back, and the under surface of the wing-membrane is exposed. The caudal membrane is shown of nat. size in Fig. 400.

most colossal living beings of Mesozoic time, and, indeed, so far as we know, of any time, belonged to the ancient order of Deinosaurs, which now attained their maximum development. In these animals, which appeared in the earliest Mesozoic ages, ordinary reptilian characters (as already remarked) were united to others, particularly in the hinder part of the skeleton, like those of birds. It was during the Jurassic period that the Deinosaurs reached their culmination in size, variety, and abundance. The most important European Jurassic genera are *Compsognathus*, *Megalosaurus* (Fig. 398), and *Cetiosaurus*. In *Compsognathus*, from the Solenhofen Limestone, the bird-like affinities are strikingly exhibited, as it possessed a long neck, small head, and long hind limbs on which it must have hopped or walked. The *Megalosaurus* of the Stonesfield Slate is estimated to have had a length of 25 feet, and to have weighed two or three tons. It frequented the shores of the lagoons, walking probably on its massive hind legs, and feeding on the mollusks, fishes, and perhaps the small mammals of the district. Still more gigantic was the *Cetiosaurus*, which, according to Phillips, probably reached, when standing, a height of not less than 10 feet and a length of 50 feet. It seems to have been a marsh-loving or river-side animal, living on the ferns, cycads, and conifers among which it dwelt.

But these monsters of the Old World were surpassed in dimensions by some discovered in the Jurassic formations of Colorado. Of these, *Brontosaurus* was distinguished by its relatively short body, long neck and tail, and remarkably small head. Its legs and feet were massive, with solid bones, and made footprints each measuring about a square yard in area. Its length is estimated at 50 feet or more, and its weight, when alive, at more than 20 tons. In habit it was more or less amphibious, probably feeding on aquatic plants or other succulent vegetation. The small head and brain and slender neural cord indicate a stupid, slow-moving reptile.[1] *Stegosaurus* had a remarkably small skull with short massive jaws, very short, powerful fore-limbs, with comparatively long and slender hind-limbs. But its most singular character was the possession of numerous dermal spines, some of great size and power, and many bony plates of various sizes and shapes, some of them more than 3 feet in diameter. Thus armed as well as protected, it must have been one of the most uncouth monsters that haunted the waters of the time. Yet it was itself herbivorous, and appears to have been more or less aquatic in habit.[2] But the most colossal of all these forms, and, indeed, the most gigantic creature yet known, was that to which Professor Marsh has given the name of *Atlantosaurus*. It was built on so huge a scale that its femur alone is more than 8 feet high, the corresponding bone of the most gigantic elephant looking like that of a dwarf, when put beside this fossil. The whole length of the animal is supposed to have been not much short of 100 feet, with a height of 30 feet or more. Contemporaneous with these huge creatures, however, there existed in Jurassic time in North America diminutive forms having such strong avian affinities that their separate bones cannot be distinguished from those of birds. Professor Marsh, who has brought these interesting forms to light, regards them as having been in some cases probably arboreal in habit, with possibly at first no more essential difference from the birds of their time than the absence of feathers.[1]

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[1] Marsh, *Amer. Journ. Sci.* xxvi. (1883) p. 81.

[2] Marsh, *op. cit.* xix. (1880) p. 258.

The oldest known bird, *Archæopteryx* (Fig. 402), comes from the Solenhofen Limestone in the Upper Jurassic series—a rock which has been especially prolific in the fauna of the Jurassic period. This interesting organism, which was rather smaller than a crow, united some of the characters of reptiles with those of a true bird. Thus it possessed biconcave vertebræ, a well-ossified broad sternum, and a long lizard like tail, each vertebra of which bore a pair of quill-feathers. The three wing-fingers were all free and each ended in a claw, and there appear to have been four toes to each foot, as in most of our common birds. The jaws carried true teeth, as in the toothed birds found in the Cretaceous rocks of Kansas.[2] Remains of birds have likewise been obtained from the Upper Jurassic rocks (Atlantosaurus-beds) of Wyoming Territory in Western America. The best preserved of these has been named by Marsh *Laopteryx*, which he believes to have possessed teeth and biconcave vertebræ.[3]

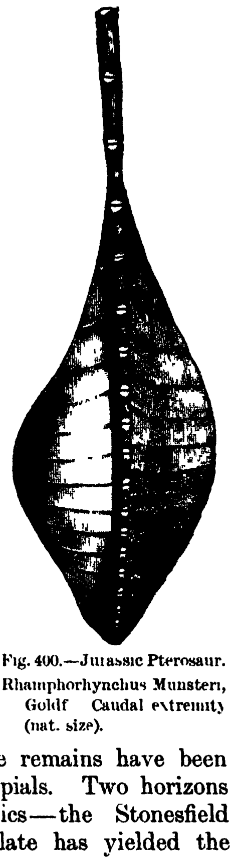

Fig. 400.—Jurassic Pterosaur. Rhamphorhynchus Munsteri, Goldf Caudal extremity (nat. size).

The most highly organised animals of which the remains have been discovered in the Jurassic system are small marsupials. Two horizons in England have furnished these interesting relics—the Stonesfield Slate and the Purbeck beds. The Stonesfield Slate has yielded the remains of five genera—*Amphitylus*, *Amphilestes*, and *Phascolotherium* (Fig. 403), probably insectivorous, the latter being related to the living American opossums; *Amphitherium*, resembling most closely the Australian *Myrmecobius*; and *Stereognathus*, which Owen was disposed to think was rather a placental, hoofed, and herbivorous form. Higher up in the English Jurassic series another interesting group of mammalian remains has been obtained from the Purbeck beds, whence upwards of twenty species have been exhumed belonging to eleven genera (*Spalacotherium*, *Amblotherium*, *Peralestes*, *Achyrodon*, *Kurtodon*, *Peramus*, *Stylodon*, *Bolodon*, *Triconodon*, *Triacanthodon*, Fig. 404), of which some appear to have been insectivorous, with their closest living representatives among the Australian phalangers and American opossums, while one, *Plagiaulax*, resembling the Australian kangaroo-rats (*Hypsiprymnus*), is held by Owen to have been a carnivorous form.[1] A still more varied and

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[1] For Prof. Marsh's descriptions of Jurassic Deinosaurs see *Amer. Journ. Sci.* xvi. (1878) p. 411; xvii. (1879) p. 86; xviii. (1880); xix. (1880) p. 253; xxi. (1881) p. 417; xxii. (1881) p. 340; xxiii. (1882) p. 81; xxvi. (1883) p. 81; xxvii. (1884) p. 161; xxxiv. (1887) p. 413; xxxvii. (1889) pp. 323, 331; xxxix. (1890) p. 415; xlii. (1891) p. 179; xliv. (1892) p. 347.

[2] See Marsh, *Amer. Journ. Sci.* Nov. 1881, p. 337; *Geol. Mag.* 1881, p. 485; Carl Vogt, *Rev. Sci.* Sept. 1879; Seeley, *Geol. Mag.* 1881, pp. 300, 454; W. Dames, *Sitzb. Berlin Akad.* xxxviii. (1882) p. 817; *Geol. Mag.* 1882, p. 566; 1884, p. 418.

[3] *Amer. Journ. Sci.* xxi. (1881) p. 341; also xxii. p. 337.

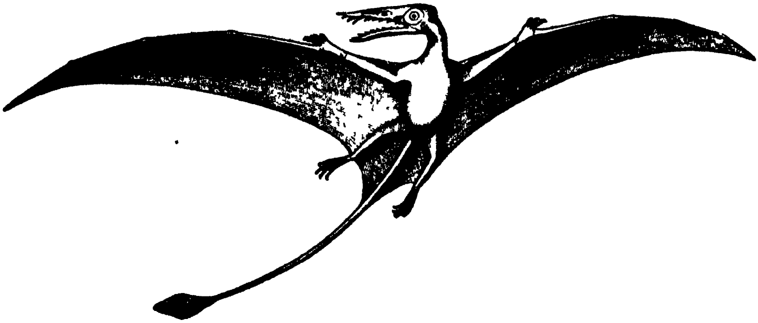

Fig. 401.—Jurassic Pterosaur.
Rhamphorhynchus Munsteri (¼), restored by Marsh.

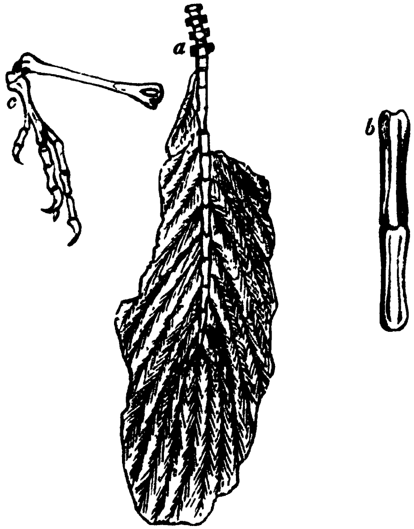

Fig. 402.—Bird (Archæopterix macrura, Owen)—Solenhofen Limestone (Middle Jurassic).
a, Tail and Tail-feathers (¼); *b*, caudal vertebræ (nat. size); *c*, foot (¼).

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[1] See Falconer, *Q. J. Geol. Soc.* xiii. 261 ; xviii. 348 ; Owen, "Monograph of Mesozoic Mammals," *Palæontograph. Soc.* 1871 ; 'Extinct Mammals of Australia,' 1877.

abundant assemblage of mammalian remains has been exhumed from the Jurassic rocks of the western regions of the United States (p. 919).

GEOGRAPHICAL DISTRIBUTION.—The Jurassic system covers a vast area in Europe. Beginning at the west, remnants of it occur in the far north of Scotland. It ranges across England as a broad band from the coasts of Yorkshire to those of Dorset. Crossing the Channel, it encircles with a great ring the Cretaceous and Tertiary basin of the north of France, whence it ranges on the one side southwards down the valleys of the Saone and Rhone, and on the other round the old crystalline nucleus of Auvergne to the Mediterranean. Eastwards, it sweeps through the Jura Mountains (whence its name is taken) up to the high grounds of Bohemia. It forms part of the outer ridges of the Alps on both sides, rises along the centre of the Apennines, and appears here and there over the Spanish peninsula. Covered by more recent formations, it underlies the great plain of northern Germany, whence it ranges eastwards and occupies large tracts in central and eastern Russia. Some years ago, Neumayr, following up the early generalisation of L. von Buch, showed that three distinct geographical regions of deposit, marking diversities of climate, can be made out among the Jurassic rocks of Europe.[1] (1) The Mediterranean province, embracing the Pyrenees, Alps, and Carpathians, with all the tracts lying to the south. One of the biological characters

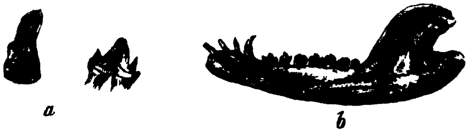

Fig. 403.—Marsupial from the Stonesfield Slate.
Phascolotherium Bucklandi, Broderip: *a*, teeth, magnified; *b*, jaw, nat. size.

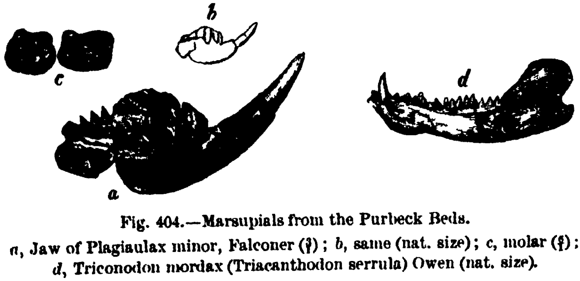

Fig. 404.—Marsupials from the Purbeck Beds.
a, Jaw of Plagiaulax minor, Falconer ($\frac{3}{1}$); *b*, same (nat. size); c, molar ($\frac{4}{1}$);
d, Triconodon mordax (Triacanthodon serrula) Owen (nat. size).

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[1] Neumayr, "Jura-Studien," *Jahrb. Geol. Reichsanstalt*, 1871, pp. 297, 451; *Verhandl. Geol. Reichsanst.* 1871, p. 165; 1872, p. 54; 1873, p. 288. "Uber climatische Zonen wahrend der Jura- und Kreidezeit," *Denksch. Wien. Akad.* xlvii. (1883) p. 277. 'Die geographische Verbreitung der Juraformation,' *op. cit.* l. (1885) p. 57. In these memoirs the student will find much interesting speculation regarding zoological distribution, organic progress and vicissitudes of climate during the Jurassic and Neocomian periods. The last memoir contains two suggestive maps of Jurassic geography.

of this area was the great abundance of Ammonites belonging to the groups of *Heterophylli* (*Phylloceras*) and *Fimbriati* (*Lytoceras*), and the presence of forms of *Terebratula* of the family of *T. diphya* (*janitor*). (2) The central European province, comprising the tracts to the north of the Alpine ridge, including France, England, Germany, and the Baltic countries, and marked by the comparative rarity of the Ammonites just mentioned, which are replaced by others of the genera *Aspidoceras* and *Oppellia*, and by abundant reefs and masses of coral. (3) The boreal or Russian province, comprising the middle and north of Russia, Petschora, Spitzbergen, and Greenland. The life in this area was less varied than in the others; in particular, the widely distributed species of *Oppellia* and *Aspidoceras* of the middle-European province are absent, as well as large masses of corals, showing that in Jurassic times there was a perceptible diminution of temperature towards the north.

Neumayr subsequently extended these three provinces into homoiozoic zones or belts stretching round the globe, and showing the probable distribution of climate and life during Jurassic and early Cretaceous times. (1) The Boreal Zone descends as far as lat. 46° in North America, whence it bends north-eastwards, coming as high as lat. 63° in Scandinavia; but then taking a remarkable bend towards the south-east across Russia, the Kirghiz Steppes and Turkestan into Tibet, about lat. 29° N. and long. 85° E. This curious projection is explained by the fact that the fauna of the Jurassic rocks of Tibet, Kashmir and Nepal, though peculiar, has greater affinities with that of the boreal than with that of more southern zones. The boreal zone is divisible, as far as yet known, into three provinces, the Arctic, Russian and Himalayan. (2) The North Temperate Zone reaches to about lat. 33° in North America. In Europe its limits are more precisely defined. It extends from Lisbon across the Spanish tableland to the west end of the Pyrenees, thence across the south of France and along the north side of the Alps to the north end of the Carpathians, bending southward so as to keep to the north of the Black Sea and Caucasus, and then striking south-eastwards into the Himalaya chain, where it is nearly cut off by the extension of the Boreal Zone just mentioned. In this zone four provinces have been recognised—the middle European, Caspian, Punjab, and Californian. (3) The Equatorial Zone extends southwards to the southern end of Peru, and does not include the extreme southern coasts of South Africa and Australia, which with the remaining part of South America, lie in the South Temperate Zone. In the Equatorial Zone, seven provinces are more or less clearly defined: the Alpine, Mediterranean, Crim-Caucasian, Ethiopian, Columbian, Caribbean (?), and Peruvian. The South Temperate Zone is allowed four provinces: the Chilian, New Zealand (?), Australian and Cape.

By carefully collecting and collating the evidence furnished by the discovery of Jurassic rocks in all parts of the world, Neumayr believed himself warranted to give a sketch of the probable geographical distribution of sea and land during the Jurassic period, and even to reduce the data to the form of maps. He thought there was sufficient proof of the existence of three great oceans partly coincident with those still existing

—the Arctic Ocean, the Pacific Ocean, and the Antarctic Ocean. A central Mediterranean stretched across the narrow part of the American Continent, and traversing what is now the North Atlantic, swept all over central and southern Europe, the present Mediterranean Sea, and the north of Africa. It joined the Arctic Ocean in the Russian plain, sent various arms into Asia, and passing across central India stretched southwards to the Antarctic Ocean. A long and wide branch extended between Africa and a supposed mass of land connecting southern Africa, Madagascar, and southern India. The chief terrestrial areas of the period, according to Neumayr, were the African-Brazilian continent, extending across the southern Atlantic; the Chinese-Australian continent, extending from the north of China over the south-east of Asia to Tasmania and New Zealand; the Nearctic continent, extending from south-eastern Greenland and Iceland across the North Atlantic to the Gulf of Mexico; the Scandinavian island, the European Archipelago, consisting of numerous insular tracts dotted over the Jurassic sea from Ireland on the west to southern Russia on the east; the Turanian island, lying to the east of the Caspian; and the Ural island, on the site of the Ural Mountains. But much of this geography rests on slender evidence. One of the most remarkable facts pointed out by Neumayr is the extent of the overlap of upper Jurassic rocks upon lower members of the system. He showed that the Lias was not deposited over an enormous part of the earth's surface, which nevertheless sank beneath the sea wherein later parts of the Jurassic series were laid down.

§ 2. Local Development.

Britain.[1]—The stratigraphical succession of the Jurassic rocks was first worked out in England by William Smith, in whose hands it was made the foundation of stratigraphical geology. The names adopted by him for the subdivisions he traced across the country have passed into universal use, and, though some of them are uncouth English provincial names, they are as familiar to the geologists of other countries as to those of England.

The Jurassic formations stretch across England in a varying band from the mouth of the Tees to the coast of Dorsetshire. They consist of sands, sandstones and limestones interstratified with softer clays and shales. Hence they give rise to a characteristic type of scenery,—the more durable and more porous beds standing out as long ridges, sometimes even with low cliffs, while the clays underlie the level spaces between. Arranged in descending order, the following subdivisions of the English Jurassic system are generally recognised:—

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[1] For British Jurassic rocks the student's attention may be specially called to Phillips' 'Geology of Oxford and the Thames Valley'; Tate and Blake's 'Yorkshire Lias'; Hudleston's "Yorkshire Oolites," in *Geol. Mag.* 1880-84, and *Proc. Geol. Assoc.* vols. iii. to v.; Memoirs published by the Palæontographical Society, particularly Morris and Lycett's 'Mollusca from Great Oolite'; Davidson's 'Tertiary, Oolitic, and Liassic Brachipoda'; Wright's 'Oolitic Echinodermata' and 'Lias Ammonites'; Owen's 'Mesozoic Reptiles'; 'Mesozoic Mammals,' 'Wealden and Purbeck Reptiles'; Hudleston's 'British Jurassic Gasteropoda'; Buckman's 'Inferior Oolite Ammonites.' The *Memoirs of the Geological Survey* comprise some important works on this subject, such as Hull's 'Geology of Cheltenham'; Judd's 'Geology of Rutland,' &c.; H. B. Woodward's 'Jurassic Rocks of England and Wales (Yorkshire excepted)'; C. Fox-Strangway's 'Jurassic Rocks of Yorkshire,' &c. Further information will be found in the Address by Mr. Etheridge, *Q. J. Geol. Soc.* 1882; in Woodward's 'Geology of England and Wales'; and in other memoirs cited below. See also Oppel's 'Juraformation Englands, Frankreichs und Deutschlands,' 1856; Quenstedt's 'Der Jura,' 1858.

Formations or Series.	Groups or Stages.	Sub-groups or Sub-stages.	Maximum thicknesses. Feet.
Upper or Portland Oolites.	Purbeckian	Upper fresh-water beds Middle marine beds Lower fresh-water beds	360
	Portlandian	Portland Stone	70
		Portland Sands	150
	Kimeridgian	Kimeridge Clay	600
Middle or Oxford Oolites.	Corallian	Coral Rag, Coralline Oolite, and Calcareous Grit	250
	Oxfordian	Oxford Clay and Kellaways Rock	600
Lower Oolites.	Great or Bath Oolite group	Cornbrash. This forms a persistent band at the top of the lower or variable (marine and estuarine) group	25
		Bradford Clay and Forest Marble	160
		Great or Bath Oolite, with Stonesfield Slate	130
	Fuller's Earth	Fuller's Earth	150
	Inferior Oolite	Cheltenham beds (thick estuarine series of Yorkshire, representing the whole succession up to the base of the Cornbrash)	270
		Northampton Sands ("Dogger" of Yorkshire)	160
		Midford Sands (passage beds)	
Lias.	Upper Lias		400
	Marlstone		350
	Lower Lias		900

Although these names appear in tabular order, as expressive of what is the predominant or normal succession of strata, considerable differences occur when the rocks are traced across the country, especially in the Lower Oolites. Thus the Inferior Oolite consists of marine limestones and marls in Gloucestershire, but chiefly of massive estuarine sandstones and shales in Yorkshire. These differences help to bring before us some of the geographical features of the British area during the Jurassic period.

The Lias,[1] consists of three stages or groups, well marked by physical and palæontological characters.[2] In the Lower member, numerous thin blue and brown limestones, with partings of dark shale, are surmounted by similar shales with occasional nodular limestone bands. The Middle Lias consists of argillaceous and ferruginous limestones (Marlstone) with underlying micaceous sands and clays. In some of the midland counties, but more especially in Yorkshire, this subdivision is remarkable for containing a thick series of beds of earthy carbonate of iron (Ironstone series), which has been extensively worked in the Cleveland district. The Upper stage is composed of clays and shales with nodules of limestone, surmounted by sandy deposits, which are perhaps best classed with the Inferior Oolite. In Yorkshire it consists of about 240 feet of grey and black shale, in the upper part of which lies a dark band full of pyritous "doggers" (ironstone concretions) and blocks of jet, which are extracted for the manufacture of ornaments. This jet appears to have been originally water-logged fragments of coniferous wood.[1]

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[1] This word, now so familiar in geological literature, was adopted by William Smith, who found it given by the Somerset quarrymen to the "layers" of argillaceous limestone forming a part of the series of rocks to which the term is now applied.

[2] The English Lias is fully described by Mr. H. B. Woodward in his monograph in the *Memoirs of the Geological Survey* above cited.

These three stages are subdivided into the following zones according to distinctive species of Ammonites, though the zones are not so definite in nature as in palæontological lists :[2]—

Upper Lias.	2.	Zone of Ammonites	(Stephanoceras) communis.
	1.	„	(Harpoceras) serpentinus.
Middle Lias.	2.	„	(Amaltheus) spinatus.
	1.	„	„ margaritatus.
Lower Lias.	10.	„	(Ægoceras) Henleyi.
	9.	„	(Amaltheus) Ibex.
	8.	„	(Ægoceras) Jamesoni.
	7.	„	(Arietites) raricostatus.
	6.	„	(Amaltheus) oxynotus.
	5.	„	(Arietites) obtusus.
	4.	„	„ Turneri.
	3.	„	„ Bucklandi.
	2.	„	(Ægoceras) angulatus.
	1.	„	„ planorbis.

resting conformably on *Avicula contorta* beds (p. 867).

The organic remains of the British Lias now include nearly 300 genera and more than six times that number of species. The plants comprise leaves and other remains of cycads (*Palæozamia, Otozamites*), conifers (*Pinites, Clathropteris, Peuce*), ferns (*Alethopteris*, &c.), and mares' tails (*Equisetites*). These fossils serve to indicate the general character of the flora, which seems now to have been mainly cycadaceous and coniferous, and to have presented a great contrast to the lycopodiaceous vegetation of Palæozoic times. The occurrence of land-plants dispersedly throughout the English Lias shows also that the strata, though chiefly marine, were deposited within such short distance from shore, as to receive from time to time leaves, seeds, fruits, twigs, and stems from the land. Further evidence in the same direction is supplied by the numerous insect remains, which have been obtained principally from the Lower Lias. These were, no doubt, blown off the land and fell into shallow water, where they were preserved in the silt on the bottom. The *Neuroptera* are numerous, and include several species of *Libellula.* The coleopterous forms comprise a number of herbivorous and lignivorous beetles (*Elater, Buprestites*, &c.) There were likewise representatives of the orthopterous, dipterous, and palæodictyopterous orders. These relics of insect life are so abundant in some of the calcareous bands that the latter are known as insect-beds.[3] With them are associated remains of terrestrial plants, cyprids, and mollusks, sometimes marine, sometimes apparently brackish-water. The marine life of the period has been abundantly preserved, so far at least as regards the comparatively shallow and juxta-littoral waters in which the Liassic strata were accumulated.[4] Foraminifera abounded on some of the sea-bottoms, the genera *Cristellaria*, *Dentalina*, *Marginulina*, *Frondi*-*cularia*, *Polymorphina*, and *Planularia* being the more important. Corals, though on the whole scarce, abound on some horizons (*Astrocœnia*, *Thecosmilia*, *Isastræa*, *Montli*-

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[1] C. Fox-Strangways, *Mem. Geol. Survey*, "Scarborough and Whitby" (1882), p. 21.

[2] Wright on Liassic Ammonites, *Palæontograph. Soc.* and *Q. J. Geol. Soc.* xvi. 374 ; C. H. Day, *op. cit.* xix p. 278 ; Etheridge, *op. cit.* xxxviii. (Address). As the zones are not generally defined by lithological features they cannot be satisfactorily mapped. On the maps of the Geological Survey the base of the Middle Lias is perhaps not drawn uniformly at one palæontological horizon ; but it generally corresponds with the base of the Margaritatus zone. (See Judd, 'Geology of Rutland,' pp. 45, 89.)

[3] Brodie, *Proc. Geol. Soc.* 1846, p. 14 ; *Q. J. Geol. Soc.* v. 31 ; 'History of Fossil Insects,' 1846. See Scudder, *Bull. U.S. Geol. Surv.* No. 71 (1891), pp. 98-236, for a list of all known Mesozoic insects, and references to the authorities for the description of each species.

[4] See R. Tate, "Census of Lias Marine Invertebrata," *Geol. Mag.* viii. p. 4.

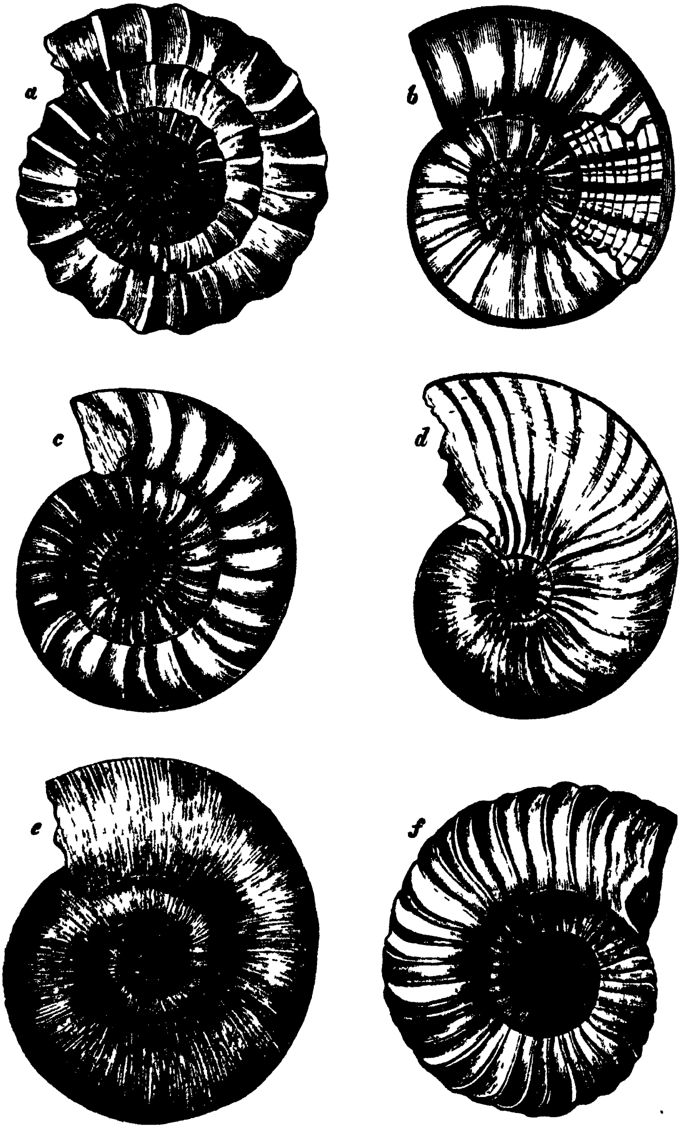

Fig. 405.—Lower Lias Ammonites.

a, Ammonites (Arietites) raricostatus, Zeit. (¾); *b*, A. (A.) obtusus, Sby. (½); *c*, A. (A.) Bucklandi, Sby. (¼); *d*, A. (Amaltheus) oxynotus, Quenst. (⅔); *e*, A. (Ægoceras) planorbis, Sby.; *f*, A. (Æ.) angulatus, Schloth. (½).

valtia, Septastræa, &c.) The crinoids were represented by thick growths of *Extracrinus* and *Pentacrinus.* There were brittle-stars, star-fishes, and sea-urchins (*Ophioglypha, Uraster, Luidia, Hemipedina, Cidaris, Acrosalenia*)—all generically distinct from those of the Palæozoic periods. The annelides were represented by *Serpula, Vermilia,* and *Ditrupa.* Among the crustacea, the more frequent known genera are *Eryon* (entirely Liassic), *Glyphæa* (from Lower Lias to Kimeridge clay), and *Eryma.* The brachiopods are chiefly *Rhynchonella, Waldheimia, Spiriferina, Thecidium,* and *Terebratula. Spiriferina* is the last of the Spirifers, and with it are associated the last forms of *Leptæna,* of which five Liassic species are known from English localities (Fig. 388). Of the lamellibranchs a few of the most characteristic genera are *Pecten, Lima, Avicula, Gryphæa, Gervillia, Ostrea, Plicatula, Mytilus, Cardinia, Leda, Cypricardia, Astarte, Pleuromya, Hippopodium,* and *Pholadomya.* Gasteropods, though usually rare in such muddy strata as the greater part of the Lias, occasionally occur, but most frequently in the calcareous zones. The chief genera are *Cerithium, Turbo, Trochus, Pleurotomaria, Chemnitzia,* and *Turritella.* The cephalopods, however, are the most abundant and characteristic shells of the Lias ; the family of the Ammonites numbers upwards of 300 species in the British Lias. Many of these are the same as those that have been found in the Jurassic series of Germany, and they occupy on the whole the same relative horizons, so that over central and western Europe it has been possible to group the Lias into the various zones given in the table (p. 899). Of the genus *Nautilus* about ten species have been found. The dibranchiate cephalopods are represented by more than 60 species of the genus *Belemnites.*

From the English Lias numerous species of fishes have been obtained. Some of these are known only by their teeth (*Acrodus*), others by both teeth and spines (*Hybodus*). The ganoids are frequently found entire ; *Dapedius, Pholidophorus, Æchmodus, Pachycormus, Eugnathus,* and *Leptolepis* are the most frequent genera. But undoubtedly the most remarkable palæontological feature in this group of strata is the number and variety of its reptilian remains. The genera *Ichthyosaurus, Plesiosaurus, Dimorphodon, Scelidosaurus, Teleosaurus,* and *Steneosaurus* have been recovered, in some cases the entire skeleton having been found with almost every bone still in place. The two genera first mentioned are especially frequent, and more or less perfect skeletons of them are to be seen in most public museums.

The Lias extends continuously across England from the mouth of the Tees to the coast of Dorsetshire. It likewise crosses into South Wales. Interesting patches occur in Shropshire and at Carlisle, far removed from the main mass of the formation. A considerable development of the Lias stretches across the island of Skye, and skirts adjoining tracts of the west of Scotland, where the shore-line of the period is partly traceable ; while small portions of the lower division of the formation are exposed on the foreshore of the east of Sutherland, near Dunrobin. In the north of Ireland, also, the characteristic shales appear in several places from under the Chalk escarpment.

The LOWER OOLITES lie conformably upon the top of the Lias, with which they are connected by a general similarity of organic remains, and by about 45 species which pass up into them from the Lias. In the south-west and centre of England they chiefly consist of shelly marine limestones, with clays and sandstones ; but, traced northwards into Northampton, Rutland, and Lincolnshire, they contain not only marine limestones, but a series of strata indicative of deposit in the estuary of some river descending from the north, for, instead of the abundant cephalopods of the truly marine and typical series, we meet with fresh-water genera such as *Cyrena* and *Unio,* estuarine or marine forms such as *Ostrea* and *Modiola,* thin seams of lignite, thick and valuable deposits of ironstone, and remains of terrestrial plants. These indications of the proximity of land become still more marked in Yorkshire, where the strata (800 feet thick) consist chiefly of sandstones, shales with seams of ironstone and coal, and occasional horizons containing marine shells. It is deserving of notice that the Cornbrash, at the top of the Lower Oolite in the typical Wiltshire district, though rarely 20 feet thick, runs across the country from Devonshire to Lincolnshire and Yorkshire. Thus a distinctly defined series of beds of an estuarine character is in the north homotaxially representative of the marine formations of the south-west. At the close of the Lower Oolitic period

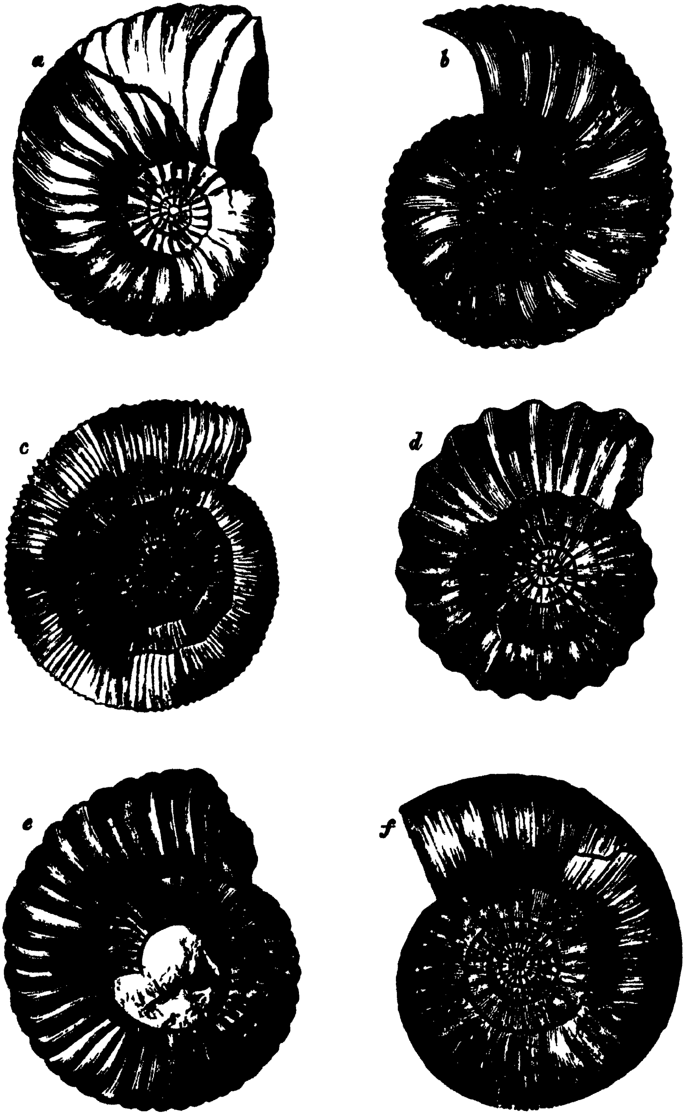

Fig. 406.—Middle and Lower Lias Ammonites.

a, Ammonites (Amaltheus) margaritatus, Mont. (½); *b*, A. (A.) spinatus, Brug. (½); *c*, Davœi, Sby. (½); *d*, A. (Æ.) capricornus, Schloth. (½), *e*, A. (Æ.) Jamesoni, Sby. (½). *f*, A. (Æ.) brevispina, Sby. (½).

the estuary of the northern tract was submerged, and marine deposits were laid down across England.

The English Lower Oolites show considerable local variation in their subdivisions. They are typically developed in the south-western counties, but the limestones and clays pass laterally into sands. The lowest group, that of the **Midford Sands**, is sometimes placed with the Lias. It consists of yellow micaceous sands, with some concretionary sandstone and sandy limestone, and ranges from 25 to 200 feet in thickness. A ferruginous limestone at the top contains so many Ammonites, Belemnites, and Nautili, that it has been called the "Cephalopoda bed." Two Ammonite zones may be recognised in this group, viz.:—

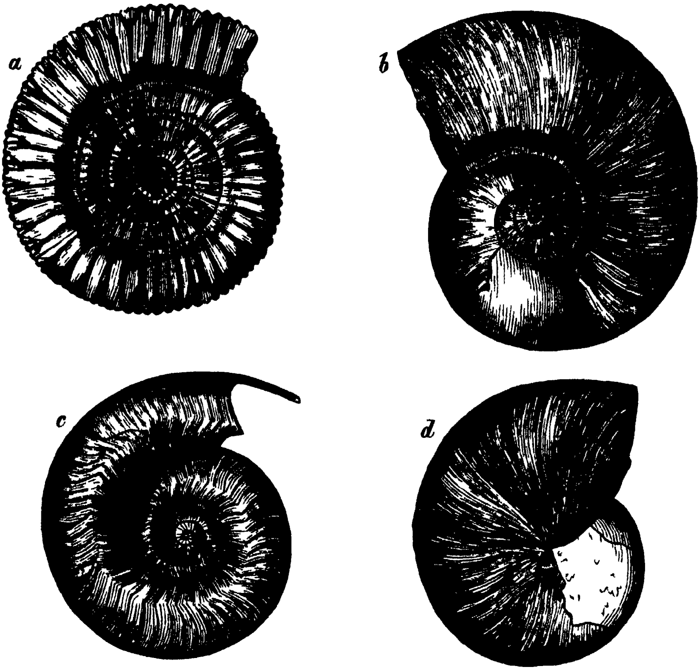

Fig 407.—Upper Lias Ammonites.

a, Ammonites (Stephanoceras) communis, Sby ($\frac{3}{4}$); *b*, A (Lytoceras) jurensis, Zieten ($\frac{1}{12}$); *c*, A. (Harpoceras) serpentinus, Reinecke ($\frac{1}{4}$); *d*, A (Phylloceras) heterophyllus, Sby. ($\frac{1}{3}$).

Zone of Ammonites (Harpoceras) opalinus.
" " (Lytoceras) jurensis.

Among the other characteristic fossils are *Ammonites aalensis*, *A. hircinus*, *A. radians*, *A. variabilis*, *Belemnites compressus*, *B. irregularis*, *Gresslya abducta*, *Trigonia formosa*, *Gervillia Hartmanni*, *Rhynchonella cynocephala*, *R. plicatella*, &c.

The **Inferior Oolite** (Bajocian) attains its maximum development in the neighbourhood of Cheltenham, where it has a thickness of 264 feet, and consists of calcareous freestone and ragstone or grit. It presents a tolerably copious suite of invertebrate remains, which resemble generically those of the Lias. The corals include species of *Isastræa*, *Montlivaltia*, and other genera. The crinoids are represented by *Pentacrinus*; the star-fishes by species of *Astropecten*, *Goniaster*, *Solaster*, and *Stellaster*; the sea-urchins by species of *Acrosalenia*, *Cidaris*, *Hemipedina*, *Clypeus*, *Pygaster*, &c. The predominance of *Rhynchonella* and *Terebratula* over the rest of the brachiopods becomes still more marked. *Lima*, *Ostrea*, *Pecten*, *Pinna*, *Astarte*, *Cucullæa*, *Myacites*, *Mytilus*, *Pholadomya*, *Trigonia* are the most common genera of lamellibranchs. The gasteropods are abundant, especially in the genera *Pleurotomaria*, *Alaria*, *Trochus*, *Turbo*, *Nerinæa*, *Cerithium*, and *Pseudomelania*. Ammonites, Nautili, and Belemnites are of frequent occurrence. Palæontologically the Inferior Oolite has been subdivided into the following zones in descending order:[1]—

Zone of Ammonites (Cosmoceras) Parkinsoni (*A. subradiatus*, *Terebratula globata*, *Rhynchonella subtetrahedra*, &c.)
Zone of Ammonites (Stephanoceras) humphriesianus (*A. Blagdeni*, *A. Martinsii*, *Waldheimia carinata*, &c.)
Zone of Ammonites (Harpoceras) Murchisonæ, with sub-zone of *A. Sowerbyi* in upper part (*A. concavus*, *Terebratula fimbria*, *T. simplex*, *T. plicata*, &c)

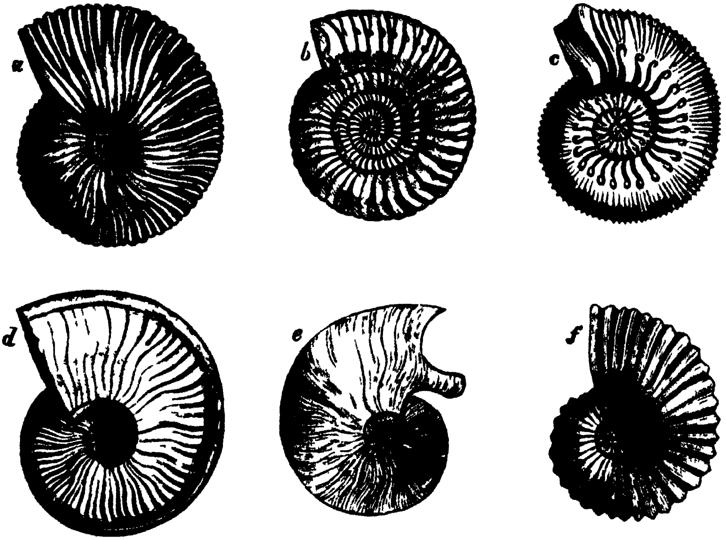

Fig. 408.—Lower Oolite Ammonites.

a, Ammonites (Stephanoceras) macrocephalus, Schloth. (⅓), *b*, A. (Cosmoceras) Parkinsoni, Sby. (½). *c*, A. (Stephanoceras) humphriesianus, Sby. (¼); *d*, A. (Harpoceras) Murchisonæ, Sby. (⅓); *e*, A (Harpoceras) opalinus, Rein (½); *f*, A. (Lytoceras) torulosus, Ziet. (⅓).

The component strata of the group are subject to great variations in thickness and lithological character. The thick marine series of Cheltenham is reduced in a distance of 30 or 40 miles to a thickness of a few feet. The limestones pass into sandy strata, so that in parts of Northamptonshire the whole of the formations between the Upper Lias Clay and the Great Oolite consist of sands with beds of ironstone, known as the Northampton Sand. The higher portions of the sandy series contain estuarine shells (*Cyrena*) and remains of terrestrial plants. In Yorkshire the Great Oolite series disappears (unless its upper part is represented by the Upper Estuarine series of that district) while the Inferior Oolites swell out into a great thickness and are composed of the following subdivisions in descending order:[2]—

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[1] On the Ammonites of these zones, see S. S. Buckman, *Q. J. Geol. Soc.* 1881, p. 588.

[2] Phillips' 'Geology of Yorkshire,' Hudleston, *Geol. Mag.* 1880, p. 246; 1882, p. 146;

		Feet.
Inferior Oolite or "Bajocian."	Upper Estuarine series, shales and sandstones resting on a thick sandstone (Moor Grit) more than	200
	Scarborough or Grey Limestone series, consisting of grey calcareous and siliceous bands with shaly partings (*Belemn. giganteus, Amm. humphriesianus, Amm. Blaydeni,* &c.)	3–100
	Middle Estuarine series, chiefly shales, with three or four beds of sandstone full of plant-remains. This is the chief coal-bearing zone of the Lower Oolites. A few thin coal-seams occur, only two of which have been found worth working; none of them exceed 18 inches or 2 feet in thickness	50–100
	Millepore bed, a ferruginous or calcareous grit passing into a sandy limestone (*Ammonites Sowerbyi*)	10–40
	Lower Estuarine series, consisting of an upper group of false-bedded ferruginous sandstones with carbonaceous matter, separated by some ironstone bands from a lower group of carbonaceous shales and sandstones with thin coal-seams	300
	Dogger—ferruginous sandstone and sandy ironstone passing down into the Jurensis-beds (Midford Sands) (*Ceromya bajociana, Amm. Murchisonæ, A. aalensis,* &c.)	40–95

A tolerably abundant fossil flora has been obtained from these Yorkshire beds. With the exception of a few littoral fucoids, all the plants are of terrestrial forms. Among them are more than 50 species of ferns (*Pecopteris, Sphenopteris, Phlebopteris,* and *Tæniopteris* being characteristic). Next in abundance come the cycads, of which above 20 species are known (*Otozamites, Zamia, Pterophyllum, Cycadites*). Coniferous remains are not infrequent in the form of stems or fragments of wood, as well as in occasional twigs with attached leaves (*Araucarites, Brachyphyllum, Thuyites, Peuce, Walchia, Cryptomerites, Taxites*).

The Fuller's Earth is an argillaceous deposit which, extending from Dorsetshire to the neighbourhood of Bath and Cheltenham, attains a maximum depth of nearly 150 feet, but dies out in Oxfordshire, and is absent in the eastern and north-eastern counties. Among its more abundant fossils are *Ammonites subcontractus, Goniomya literata, Ostrea acuminata, Rhynchonella varians,* and *Waldheimia ornithocephala*; but most of its fossils occur also in the Great and Inferior Oolite. The conditions for marine life over the muddy bottom on which this deposit was laid down would appear to have been unfavourable. Thus few gasteropods are known from the Fuller's Earth. The beds of economic fuller's earth are worked at Midford and Wellow near Bath; their detergent properties are due to physical characters rather than chemical composition.

The Great Oolite (Bathonian) consists, in Gloucestershire and Oxfordshire, of three sub-groups of strata: (*a*) lower sub-group of thin-bedded limestones with sands, known as the Stonesfield Slate; (*b*) middle sub-group of shelly and yellow or cream-coloured, often oolitic limestones, with partings of marl or clay—the Great Oolite proper; (*c*) upper sub-group of clays and shelly limestones, including the Bradford Clay, Forest Marble, and Cornbrash. These subdivisions, however, cease to be recognisable as the beds are traced eastward. The Bradford Clay of the upper sub-group soon disappears, and the Forest Marble, so thick in Dorsetshire, thins away in the north and east of Oxfordshire, the horizon of the group being represented in Bedfordshire, Northamptonshire, and Lincolnshire, by the "Great Oolite Clays" of that district. The Cornbrash, however, is remarkably persistent, retaining on the whole its lithological and palæontological characters from the south-west of England to the borders of the Humber. The limestones of the middle sub-group can be traced from Bradford-on-Avon to Lincolnshire. The lower sub-group, including the Stonesfield Slate, is locally developed in parts of

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Proc. Geol. Assoc. iii. iv. v. C. Fox-Strangways, "Geology of Scarborough and Whitby," *Mem. Geol. Surv.* 1882. The fullest account of the Jurassic rocks of Yorkshire will be found in the volumes by Mr. Fox-Strangways in the series on 'The Jurassic Rocks of Britain,' in the *Memoirs of the Geol. Survey* (1892).

Gloucestershire and Oxfordshire, and passes into the "Upper Estuarine series" of the Midland counties.[1]

The fossils of the Stonesfield Slate are varied and of high geological interest. Among them are about a dozen species of ferns, the genera *Pecopteris*, *Sphenopteris*, and *Tæniopteris* being still the prevalent forms. The cycads are chiefly species of *Palæozamia*, and the conifers of *Thuyites*. With these drifted fragments of a terrestrial vegetation there occur remains of beetles, dragon-flies, and other insects which had been blown or washed off the land. The waters were tenanted by a few brachiopods (*Rhynchonella concinna* and *Terebratula*), by lamellibranchs (*Gervillia acuta*, *Pholadomya acuticosta*, *Lima*, *Ostrea gregaria*, *Pecten*, *Astarte*, *Modiola*, *Trigonia*, &c.), by gasteropods (*Natica*, *Nerita*, *Patella*, *Trochus*, &c.), by a few ammonites (*A. gracilis*) and belemnites (*B. fusiformis*, *B. bessinus*), and by elasmobranch and ganoid fishes, of which about 50 species are known (*Ceratodus*, *Ganodus*, *Hybodus*, *Lepidotus*, *Pholidophorus*, *Pycnodus*, &c.) The reptiles comprise representatives of turtles, with species of *Plesiosaurus*, *Cetiosaurus*, *Teleosaurus*, *Megalosaurus*, and *Rhamphocephalus*. But the most important organic relics from this geological horizon are the marsupial mammalia already referred to.

The fauna of the Great Oolite proper is distinguished, among other characteristics, by the number and variety of its corals (including the genera *Isastræa*, *Cyathophora*, *Thamnastræa*). The echinoderms, which rank next to the ammonites in stratigraphical value, are well represented. Among the regular echinoids the most frequent forms are *Hemicidaris*, *Acrosalenia*, *Pseudodiadema*, and *Cidaris*. The irregular echinoids are represented by species of *Echinobrissus*, *Clypeus*, *Pygurus*, &c.; the asteroids by *Astropecten* and *Goniaster*; the crinoids by *Apiocrinus*, *Millericrinus*, and *Pentacrinus*. Polyzoa are abundant (*Diastopora*, *Heteropora*). The brachiopods are represented by species of *Terebratula*, *Rhynchonella*, *Waldheimia*, *Terebratella*, *Crania*, &c. Of the whole British Jurassic lamellibranchs, numbering about 100 genera and nearly 1400 species, more than half the genera, and about one-fifth of the species, are found in the Great Oolite. Specially conspicuous are the genera *Pecten*, *Lima*, *Ostrea*, *Avicula*, *Astarte*, *Modiola*, *Pholadomya*, *Trigonia*, *Cardium*, *Arca*, *Tancredia*. The characteristic gasteropods of the Great Oolite include *Actæonina*, *Nerinæa*, *Nerita*, *Purpuroidea*, *Brachytrema*, *Patella*. Species of ammonite peculiar to the Great Oolite are *Am. arbustigerus*, *A. discus* (passes to Cornbrash), *A. gracilis*, *A. micromphalus*, *A. morisea*, *A. subcontractus*, and *A. Waterhousei*. Characteristic likewise are *Nautilus Baberi*, *N. dispansus*, *N. subcontractus*, *Belemnites aripistillum*, and *B. bessinus*. Of the fishes, the genera most abundant in species are *Mesodon*, *Ganodus*, *Hybodus*, and *Strephodus*, with *Acrodus*, *Lepidotus*, *Pholidophorus*, &c. The reptilian remains include the crocodilians *Teleosaurus* and *Steneosaurus*, *Plesiosaurus*, the pterosaur *Rhamphocephalus*, and the deinosaurs *Megalosaurus*, *Cetiosaurus*, and *Cardiodon*.

The Forest Marble varies greatly in thickness and lithological character. In the north of Dorsetshire it is estimated to be 450 feet thick, but it rapidly diminishes northwards, the limestone bands being usually not more than 30 feet thick. It lies sometimes on the Great Oolite, sometimes on the Fuller's Earth. Its lower portion becomes a grey marly clay near Bradford-on-Avon, about 10 feet thick, and this argillaceous band has been separately designated the Bradford Clay. The Forest Marble contains a much diminished fauna. Among the forms peculiar to it are the echinoderms *Apiocrinus elegans*, *Astropecten Huxleyi*, *A. Phillipsii*, *Hemicidaris alpina*. The Bradford Clay of Wiltshire has long been well known for its pear-encrinites (*Apiocrinus Parkinsoni*), which are found at the bottom of the clay with their base attached to the top of the Great Oolite limestone.

The Cornbrash (a name given by W. Smith) consists of earthy limestones, which when freshly broken are blue and compact, but which under the influence of the weather break up into rubbly material. It varies from 5 to 40 feet in thickness, yet in spite of this insignificant development it is one of the most persistent bands in the English Jurassic system. It is rich in echinoderms, lamellibranchs, and gasteropods. Among its common and characteristic species are *Echinobrissus clunicularis*, *Holectypus depressus*, *Glyphæa rostrata*, *Hippothoa Smithii*, *Hinnites gradus*, *Lima rigidula*, *Ostrea flabelloides*, *Pecten vagans*, *Cardium latum*, *Leda rostralis*, *Myacites uniformis*, *Trigonia cassiope*, *Actæonina scarburgensis*, *Ceritella costata*. Its ammonites are *A. discus* and *A. macrocephalus*, the last-named ranging up into the Kellaways Rock and Oxford Clay.[1]

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[1] Judd's "Geology of Rutland," *Mem. Geol. Surv.*

The Great Oolite series in the north-east of Scotland consists mainly of sandstones and shales, with some coal-seams which were formerly worked at Brora in Sutherland. In Skye and Raasay the formation consists of a very thick estuarine series, with abundant oysters, Trigonias, Anomias, Cyrenas, Hydrobias, Cyprids, and remains of land-plants.

The MIDDLE or OXFORD OOLITES are composed of two distinct groups: (1) the Oxfordian, and (2) the Corallian.

(1) Oxfordian, divisible into two sub-groups: (*a*) a lower division of calcareous abundantly fossiliferous sandstone, known, from a place in Wiltshire, as the Kellaways Rock (Callovian). This rock-division, from 5 to more than 80 feet thick, may be traced from Wiltshire through Bedfordshire to Lincolnshire, and attains a considerable importance in Yorkshire. It contains about 200 species of fossils, of which one-third are found in lower parts of the Jurassic series, and nearly the same proportion passes upward into higher zones. Among its characteristic forms are *Avicula inæquivalvis*, *Gryphæa bilobata*, *Lima notata*, *Ostrea archetypa*, *O. striata*, *Anatina versicostata*, *Cardium subdissimile*, *Corbis lævis*, *Lucina lyrata*, *Trigonia complanata*, *T. paucicostata*, *Alaria arsinoe*, *Cerithium abbreviatum*, *Pleurotomaria arenosa*. The distinctive ammonite of this stage is *A. calloviensis*, which gives its name to a zone. Numerous other species of ammonites occur, including *A. modiolaris*, *A. gowerianus*, *A. auritulus*, *A. Bakeriæ*, *A. Baugieri*, *A. Eugenii*, *A. flexicostatus*, *A. fluctuosus*, *A. goliathus*, *A. lalandianus*, *A. Lonsdalei*, *A. planula*, *A. tatricus*, *A. Vernoni*; also *Ancyloceras calloviense*, *Nautilus calloviensis*, and *Belemnites Owenii*.

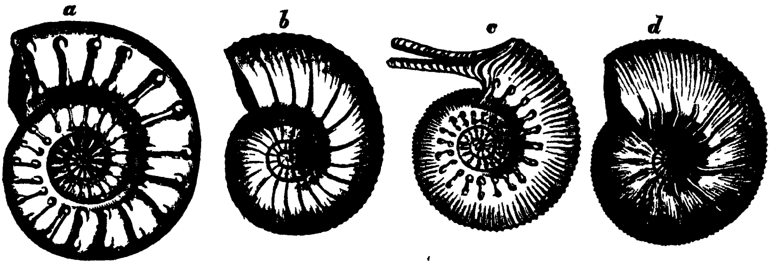

Fig. 409.—Middle Oolite Ammonites.

a, Ammonites (Aspidoceras) perarmatus, Sby. (½); *b*, A. (Amaltheus) Lamberti, Sby.; *c*, A. (Cosmoceras) Jason, Zeit. (⅓); *d*, A. (Cosmoceras) calloviensis, Sby. (½).

(*b*) The Oxford Clay—so called from the name of the county through which it passes in its course from the coast of Dorsetshire to that of Yorkshire—consists mainly of layers of stiff blue and brown clay, attaining a thickness of from 300 to 600 feet. From the nature of its material and the conditions of its deposit, this rock is deficient in some forms of life which were no doubt abundant in neighbouring areas of clearer water. Thus there are no corals, hardly any species of echinoderms, no polyzoa, and less than a dozen species of brachiopods. Some lamellibranchs are abundant, particularly *Gryphæa dilatata* and *Ostrea* (both forming sometimes wide oyster-beds), *Lima*, *Avicula*, *Pecten*, *Astarte*, *Trigonia* (*clavellata*, *elongata*, *irregularis*), *Nucula* (*N. nuda*, *N. Phillipsii*)—

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[1] Etheridge, *Q. J. Geol. Soc.* 1882, Address, p. 202.

the whole having a great similarity to the assemblages in the clayey beds of the Lower Oolite. The gasteropods are not so numerous as in the calcareous beds below, but belong mostly to the same genera. The ammonites, especially of the *Ornati*, *Dentati*, *Flexuosi*, and *Armati* groups, are plentiful,—*A. cordatus*, *A. Duncani*, *A. Elizabethæ* (*Jason*), *A. Lamberti*, *A. oculatus*, *A. ornatus*, *A. athleta* being characteristic. Two ammonite zones have been determined in this part of the group, viz. :—

Zone of Amm. cordatus (*A. Lamberti*, &c.)
,, ,, Jason (*A. ornatus*, *A. athleta*, &c.)

The belemnites, which also are common, include *B. hastatus* (found all the way from Dorsetshire to Yorkshire) and *B. puzosianus*. The fishes include the genera *Aspidorhynchus*, *Hybodus*, *Ischyodus*, and *Lepidotus*. The reptilian genera *Ichthyosaurus*, *Murænosaurus*, *Plesiosaurus*, *Pliosaurus*, and *Megalosaurus* have been noted.

(2) Corallian, traceable with local modifications from the coast of Dorset to Yorkshire. The name of this group is derived from the numerous corals which it contains. According to the exhaustive researches of Messrs. Blake and Hudleston,[1] this group when complete consists of the following subdivisions :—

6. Supra-Corallian beds—clays and grits, including the Upper Calcareous Grit of Yorkshire, and the Sandsfoot clays and grits of Weymouth.	Zone of Amm. plicatilis.
5. Coral Rag, a rubbly limestone composed mainly of masses of coral (sub-zone of *Cidaris florigemma*).	
4. Coralline Oolite, a massive limestone in Yorkshire, but dying out southwards and reappearing in the form of marl and thin limestone.	
3. Middle Calcareous Grit, probably peculiar to Yorkshire.	
2. Lower or Hambleton Oolite, not certainly recognised out of Yorkshire.	,, ,, perarmatus.
1. Lower Calcareous Grit.	

The corals are found in their positions of growth, forming massive coral-banks in Yorkshire (*Thamnastræa*, *Isastræa*, *Thecosmilia*, *Rhabdophyllia* (Fig. 384), &c.) Numerous sea-urchins occur in many of the beds, particularly *Cidaris florigemma* (Fig. 386), also *Pygurus*, *Pygaster*, *Hemicidaris*, &c. Brachiopods are comparatively infrequent. The lamellibranchs are still largely represented by species of *Avicula*, *Lima*, *Ostrea*, *Pecten*, and *Gryphæa* (*Ostrea gregaria* being specially numerous). Nearly all the species of gasteropods are peculiar to or characteristic of the Corallian stage. The distinctive ammonites are *A. ancepsalbus*, *A. babeanus*, *A. Bergeri*, *A. cadonensis*, *A. decipiens*, *A. rupellensis*, *A. plicatilis*, *A. perarmatus*, *A. pseudo-cordatus*, *A. retroflexus*, *A. Williamsoni*.

The Upper or Portland Oolites bring before us the records of the closing epochs of the long Jurassic period in England. They are divisible into three groups: (1) Kimeridgian, at the base; (2) Portlandian, and (3) Purbeckian.

(1) Kimeridgian, so named from the clay at the base of the Upper Oolites, well developed at Kimeridge, on the coast of Dorsetshire, whence it is traceable continuously, save where covered by the Chalk, into Yorkshire. It consists of dark bluish-grey shale or clay, which in Dorsetshire is in part bituminous and can be burnt. According to Mr. J. F. Blake it may be subdivided into two sub-groups :—

(*a*) Upper Kimeridgian, consisting of paper-shales, bituminous shales, cement stone, and clays, characterised by a comparative paucity of species of fossils but an infinity of individuals; perhaps 650 feet thick in Dorsetshire, but thinning away or disappearing in the inland counties. This zone is fairly comparable with the "Virgulian sub-stage" of foreign authors.

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[1] "On the Corallian Rocks of England," *Q. J. Geol. Soc.* xxxiii. p. 260.

(*b*) Lower Kimeridgian, blue or sandy clay with calcareous "doggers," representing the "Astartian sub-stage" of foreign geologists. This is the great repository of the fossils of this group.[1]

Among the more common fossils are numerous foraminifera (*Pulvulina pulchella*, *Robulina Münsteri*), also *Serpula tetragona*, *Discina latissima*, *Exogyra virgula* (Fig. 392), *E. nana*, *Astarte supracorallina*, *Thracia depressa*, *Corbula Deshayesii*, *Cardium striatulum* (Fig. 392). Upwards of 20 species of ammonite occur only in this stage; among them are *A. accipitris*, *A. alternans*, *A. Beaugrandi*, *A. flexuosus*, *A. Kapfii*, *A. lallerianus*, *A. mutabilis*, *A. Thurmanni*, *A. triplex*. Among the belemnites are *B. abbreviatus*, *B. excentricus*, *B. explanatus*, *B. nitidus*. The Kimeridge Clay derives its chief palæontological interest from the fact that it has supplied the largest number of the Mesozoic genera and species of reptiles yet found in Britain. The huge deinosaurs are well represented by *Bothriospondylus*, *Cetiosaurus*, *Cryptodraco*, *Gigantosaurus*, *Iguanodon* (*Camptosaurus*), *Megalosaurus*, *Omosaurus*; the pterosaurs by *Pterodactylus*; the plesiosaurs by *Plesiosaurus* and *Pliosaurus*; the ichthyosaurs by *Ichthyosaurus* and *Ophthalmosaurus*; chelonians by *Enaliochelys* and *Pelobatochelys*; and crocodilians by *Dakosaurus*, *Steneosaurus*, and *Teleosaurus*.[2]

In the sea-cliffs of Speeton, Yorkshire, a thick group of clays occurs, the lower part of which contains Kimeridgian fossils, while the higher portions are unmistakably Cretaceous (p. 939). Traces of a representative of the Kimeridge Clay, and possibly of the Portlandian, above, are found even as far north as the east coast of Cromarty and Sutherland, at Eathie and Helmsdale.

(2) Portlandian, so named from the Isle of Portland, where it is typically developed. This group, resting directly on the Kimeridge Clay, consists of two divisions, the Portland Sand and Portland Stone. At Portland, according to Mr. J. F. Blake, it presents the following succession of beds in descending order:[3] —

Portland Stone.	Shell limestone (Roach), containing casts of *Cerithium portlandicum* (very abundant), *Sowerbya Dukei*, *Buccinum naticoides*, and casts of *Trigonia*.
	"Whit-bed"—Oolitic Freestone, the well-known Portland stone (*Ammonites giganteus*).
	"Curf," another calcareous stone (*Ostrea solitaria*).
	"Base-bed," a building stone like the whit-bed, but sometimes containing irregular bands of flint.
	Limestone, "Trigonia bed" (*Trigonia gibbosa*, Fig. 392. *Perna mytiloides*).
	Bed (3 feet) consisting of solid flint in the upper and rubbly limestone in the lower flat.
	Band (6 feet) containing numerous flints (*Serpula gordialis*, *Ostrea multiformis*).
	Thick series of layers of flints irregularly spaced (*Ammonites boloniensis*, *Trigonia gibbosa*, *T. incurva*).
	Shell-bed abounding in small oysters and serpulæ (*Ammonites pseudogigas*, *A. triplex*, *Pleurotomaria rugata*, *P. Rozeti*, *Cardium dissimile*, Fig. 392, *Trigonia gibbosa*, *T. incurva*, *Pleuromya tellina*).
Portland Sand.	Stiff blue marl without fossils (12 to 14 feet).
	Liver-coloured marl and sand with nodules and bands of cement stone—26 feet (*Mytilus autissiodorensis*, *Pecten solidus*, *Cyprina implicata*, *Ammonites biplex*, &c.)
	Oyster-bed (7 feet) composed of *Exogyra bruntrutana*.
	Yellow sandy beds—10 feet (*Cyprina implicata*, *Arca*).
	Sandy marl (at least 30 feet) passing down into Kimeridge Clay (*Ammonites biplex*, *Lima boloniensis*, *Pecten Morini*, *Avicula octaria*, *Trigonia incurva*, *T. muricata*, *T. Pellati*, *Rhynchonella portlandica*, *Discina humphriesiana*).

Among Portlandian fossils a single species of coral (*Isastræa oblonga*) occurs;

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[1] J. F. Blake, "On the Kimeridge Clay of England," *Q. J. Geol. Soc.* xxxi.

[2] Etheridge, *Q. J. Geol. Soc.* 1882, Address, p. 221.

[3] *Q. J. Geol. Soc.* xxxvi. p. 189.

echinoderms are scarce (*Acrosalenia Königi*, &c.), there are also few brachiopods. The most abundant fossils are lamellibranchs, the best represented genera being *Trigonia* (*T. gibbosa*, *T. incurva*), *Astarte*, *Mytilus*, *Pecten*, *Lima*, *Perna*, *Ostrea*, *Cyprina*, *Lucina* (*L. portlandica*), *Cardium* (*C. dissimile*), *Pleuromya*. The most frequent gasteropod is *Cerithium portlandicum*. The ammonites include *A. giganteus*, *pseudogigas*, *boloniensis*, *gravesianus*, *pectinatus*. Fish are represented by *Gyrodus*, *Hybodus*, *Ischyodus*, and *Pycnodus*, and some of the older Jurassic reptilian genera (*Steneosaurus*, *Plesiosaurus*, *Pliosaurus*, *Cetiosaurus*, *Megalosaurus*) still appear, together with the crocodile *Goniopholis*.[1]

(3) Purbeckian.—This group, so named from the Isle of Purbeck, where best developed, is usually connected with the foregoing formations, as the highest zone of the Jurassic series of England. But it is certainly separated from the rest of that series by many peculiarities, which show that it was accumulated at a time when the physical geography and the animal and vegetable life of the region were undergoing a remarkable change. The Portland beds were upraised before the lowest Purbeckian strata were deposited. Hence, a considerable stratigraphical and palæontological break is to be remarked at this line. The sea-floor was converted partly into land, partly into shallow estuaries. The characteristic marine fauna of the Jurassic seas nearly disappeared from the area. Fresh-water and brackish-water forms characterise the great series of strata which reaches up to the Neocomian stage, and might be termed the Purbeck-Wealden series.

The Purbeckian group has been divided into three sub-groups. Of these, the lowest (95 to 160 feet) consists of fresh-water limestones and clays, with layers of ancient soil ("dirt beds") containing stumps of the trees which grew in them; the middle comprises 50 to 150 feet of strata with some marine fossils, while the highest (50 to 60 feet) shows a return of fresh-water conditions. Among the indications of the presence of the sea is an oyster-bed (*Ostrea distorta*) 12 feet thick, with *Pecten*, *Modiola*, *Avicula*, *Thracia*, &c. The fresh-water bands contain still living genera of lacustrine and fluviatile shells (*Paludina*, *Limnæa*, *Planorbis*, *Physa*, *Valvata*, *Unio*, *Cyrena*). Numerous fishes, placoid and ganoid, haunted these Purbeck waters. Many insects, blown off from the adjacent land, sank and were entombed and preserved in the calcareous mud. These include coleopterous, orthopterous, hemipterous, neuropterous, and dipterous forms (Fig. 395). Remains of several reptiles, chiefly chelonian, but including the Portlandian crocodile *Goniopholis*, and likewise some interesting dwarf crocodiles (*Theriosuchus* is computed to have been only 18 inches long), have also been discovered. The most remarkable organisms of this group of strata are the mammalian forms already noticed (p. 893), which occur almost wholly as lower jaws, in a stratum about 5 inches thick, lying near the base of the Middle Purbeck sub-group, these being the portions of the skeleton that would be most likely first to drop out of floating and decomposing carcases.

The zone of *Belemnites lateralis* in the Speeton Clay of the Yorkshire coast and the Spilsby Sandstone of Lincolnshire, are considered by Prof. A. Pavlow and Mr. G. W. Lamplugh to represent in part the Purbeck and Portland beds of the southern districts.[2]

France and the Jura.—The Jurassic system is here symmetrically developed in the form of two great connected rings. The southern ring encloses the crystalline axis of the centre and south; the northern and larger ring encircles the Cretaceous and Tertiary basin and opens towards the Channel, where its separated ends point across to the continuation of the same rocks in England. But the structure of the two areas is exactly opposite, for in the southern area the oldest rocks lie in the centre and the Jurassic strata dip outwards, while in the northern region the youngest formations lie in the centre and the Jurassic beds dip inward below them. Where the two rings unite in the middle of France they send a tongue down to the Bay of Biscay. On the eastern side of the country the Jurassic system is copiously developed, and extends thence eastwards through the Jura Mountains into Germany.

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[1] J. F. Blake, *op. cit.* and Etheridge, *op. cit.* Damon's 'Geology of Weymouth,' 1884.

[2] *Bull. Soc. Imp. des Nat. Moscou*, 1891.

The subdivisions of the Jurassic system in the north and north-west of France belonging to what has been termed the Anglo-Parisian basin, resemble generally those established in England. But in the southern half of the country, and generally in the Mediterranean province, the facies departs considerably both lithologically and palæontologically from the English type, more particularly as regards the Upper Jurassic rocks. The following table gives in descending order a summary of the distribution of the Jurassic system in France:[1]—

10. Portlandian, separated into two sub-stages. At the base lie sands and clays, equivalents of the Portland sands, or "Bononian" with *Ammonites* (*Stephanoceras*) *portlandicum*, *A. gigas*, and *Ostrea expansa*. Higher up come sands and calcareous sandstones corresponding to the Portland stone, with *Trigonia gibbosa* and *Perisphinctes transitorius*. The Purbeckian is marked by *Corbula inflexa*. The stage is best developed along the coast near Boulogne-sur-mer, where it is composed of about 75 feet of clays, sands, and sandstones, with *Acrosalenia Koenigi*, *Perna Bouchardi*, *Echinobrissus Brodiei*, *Cardium Pellati*, *Trigonia radiata*, *T. gibbosa*, *T. incurva*, &c. At the top lies a bed of limestone containing *Cyrena Pellati*, *Cardium dissimile*, and covered by a travertin with *Cypris*, which may represent the Purbeck beds. Far to the south, in Charente, some limestones containing Portlandian fossils are covered by others with *Corbula inflexa*, *Physa*, *Paludina*, &c., possibly Purbeck. Fresh-water limestones, gypsiferous marls and dolomites (about 200 feet), and containing *Corbula forbesiana*, *Physa wealdiana*, *Valvata helicoides*, *Trigonia gibbosa*, &c., occur in the Jura, round Pontarlier and near Morteau, in the valley of the Doubs.

The Upper Jurassic rocks of southern France and the southern flank of the Alps, or what has been termed the Mediterranean basin, present a facies so different from that which was originally studied in England, northern France, and Germany that much difficulty was for many years experienced in the correlation of the deposits, and much discussion has arisen on the subject. From the researches of Oppel, Benecke, Hébert, and later writers, the true meaning of the southern facies is now better understood. It appears that the divisions ranging above the Oxfordian are represented in the southern area by a singularly uniform series of limestones, indicative of long unbroken deposition in deeper water, and unvaried by those oscillations and occasional terrestrial conditions which are observable farther north. The name of Tithonian was given by Oppel to this more uniform suite of strata, which were marked by the mixed character of their cephalopods, and by their peculiar perforated brachiopods of the type of *Terebratula diphya* (*janitor*).[2] Around Grenoble, the massive limestones resting upon some marls with species belonging to the zone of *Ammonites tenuilobatus*, contain *Terebratula diphya* associated with ammonites closely linked with Neocomian types. In the Basses Cevennes, the limestones attain a thickness of from 1200 to 1400 feet. At their base lie marls and marly limestones containing *Ammonites macrocephalus*, *A. transversarius* and *A. cordatus*. A band of bluish limestone with bituminous marls (65 feet), belonging to the zone of *A. bimammatus*, represents the Corallian. Some grey limestones (260 feet), with *A. polyplocus*, contain fossils of the zone of *A. tenuilobatus*, equivalent to the Sequanian stage. These are succeeded by a massive limestone (330 feet) with *Terebratula diphya* (*janitor*) and *Amm. transitorius*, and this by a compact white limestone (500 - 650 feet) with *Terebratula moravica* (*Repellini*), *Cidaris glandifera*, corals, &c. At the top lie some limestones (200 feet) with *Terebratula diphyoides* and many ammonites (*A. Calypso*, *A. privasensis*, *A. berriasensis*, &c.)

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[1] For a detailed account of the development of the Jurassic rocks of France, see De Lapparent's 'Géologie,' 3rd edition (1893); also A. d'Orbigny's 'Paléontologie Française —Terrains Oolithiques,' 1842-50; D'Archiac, 'Paléontologie de la France,' 1868, and 'Paléontologie Française, continuée par une réunion de Paléontologistes—Terrain Jurassique,' in course of publication; Hébert, 'Les Mers anciennes et leurs Rivages, dans le Bassin de Paris,' 1857 (a most interesting and valuable essay), and numerous papers in *Bull. Soc. Géol. France*; Monographs by Loriol, Cotteau, Pellat, Royer, Tombeck; Gosselet's 'Esquisse,' cited *ante*, p. 733; J. F. Blake, *Q. J. Geol. Soc.* 1881, p. 497, gives a bibliography for N.W. France, and Barrois (*Proc. Geol. Assoc.*) gives a summary of results for the Boulonnais. For the last named district consult also Pellat, *Bull. Soc. Géol. France*, viii. (1879); Douvillé et Rigaux, *op. cit.* xix. (1891) p. 819. Rigaux, 'Notice Géologique sur le Bas Boulonnais,' Boulogne-sur-mer, 1892.

[2] For a study of the Tithonian fauna see A. Toucas, *Bull. Soc. Géol. France*, xviii. (1890) p. 560.

9. Kimeridgian = Kimeridge Clay, divided in central and northern France into the following sub-stages in ascending order: 1, Sequanian or Astartian (*Ostrea deltoidea*, zone of *Ammonites tenuilobatus*); 2, Pterocerian (*Pterocera Oceani*, zone of *Amm. acanthicus*); 3, Virgulian (*Exogyra virgula*). In Normandy, the Corallian clays with *Diceras arietinum* are covered by other clays with *Ostrea deltoidea* (Sequanian), and nodular limestone with *Pterocera Oceani* (Pterocerian), followed by blue clays and lumachelles with *Exogyra virgula* (Virgulian). In the Pays de Bray, these various strata are 330 to 400 feet thick, and are surmounted by calcareous marls, sandstone and limestone (115 - 160 feet) containing *Ostrea catalaunica*, *Anomia lævigata*, *Hemicidaris Hofmanni*, *Echinobrissus Brodiei*, *Ostrea bruntrutana*, and representing the Bononian sub-stage. The coast-section near Boulogne-sur-mer exposes a series of clays, sands, and sandstones (180 feet), from which a large series of characteristic fossils has been obtained, and which as the type section of the Bononian beds, indicate a local littoral deposit in the upper part of the Kimeridge Clay.

In the French Ardennes, the Sequanian, Pterocerian, and Virgulian sub-stages are composed of a succession of marls and limestones (500-560 feet), the Sequanian marls and lumachelles being marked by *Ostrea deltoidea*, &c., the Pterocerian limestones by *Waldheimia humeralis*, *Pterocera ponti*, &c., and the Virgulian marls by immense numbers of *Exogyra virgula*. In the Meuse and Haute Marne, a group of compact limestones, more than 500 feet thick (Calcaires de Barrois), with *Ammonites* (*Stephanoceras*) *gigas*, &c., represents the Bononian sub-stage. In Yonne, the Sequanian sub-stage consists of oolites and contains a reef of coral full of bunches of *Septastræa*, *Montlivaltia*, &c. Towards the Jura, this sub-stage (200 feet thick) consists of limestones and marls (*Astarte minima*); the Pterocerian is well developed, and shows its characteristic fossils; while the Bononian comprises the so-called "Portlandian" limestones of the Jura, its upper part becoming the yellow or red unfossiliferous "Portlandian dolomite." In the department of the Jura, the Pterocerian sub-stage contains a coral-reef, more than 300 feet thick, near Saint Claude, and farther south another occurs at Oyonnax. In the same region, the Virgulian sub-stage, composed of bituminous shales and thin lithographic limestones, has yielded numerous fishes, reptiles, and abundant cycads and ferns. The position of these beds is fixed by the occurrence of the *Exogyra virgula* below them, and of the Bononian limestones with *Nerinæa* and *Amm. gigas* above them. From what was said above under the Portlandian stage, it will be seen that the Kimeridgian appears in a totally different aspect in the Mediterranean basin, being there composed of thick limestones with a mixed assemblage of ammonites, and characterised in the higher parts by the appearance of *Terebratula diphya*.

8. Corallian, divisible into (*a*) Argovian, or zone of sponges and *Amm. canaliculatus*; (*b*) Glyptician, or zone of *Glypticus hieroglyphicus*, and (*c*) Diceratian, or zone of *Diceras arietinum*. The sub-stages *b* and *c* comprise the zone of *Amm. bimammatus*. In Normandy, the stage presents a lower assise (Trouville oolite, or zone of *Amm. Martelli*) composed of marly and oolitic limestone and black clays (*Echinobrissus scutatus*, *Trigonia major*, &c.), and an upper coral-rag with *Cidaris florigemma* and a dark marl with *Exogyra nana*; the whole passing laterally into clays (Havre). In the Ardennes, an argillaceous marl (with *Phasianella striata*) represents the Argovian division, and is surmounted by a mass of coral limestone (400-420 feet). In Haute Marne, the Corallian beds attain a thickness of 330 feet, but are mainly formed of marls, the coral beds or reefs dwindling down in that direction. South-westwards, in Burgundy, massive limestones with corals reappear, with lithographic and oolitic limestones. To the east also, in the district of Besançon, the stage is represented by 130 to 200 feet of coral-limestone with compact and oolitic bands, and sometimes with calcareous marls that abut against the sides of what were formerly coral-reefs. Some horizons in the Corallian stage are marked by the occurrence of remains of ferns and other land-plants (Saint Mihiel, in Lorraine; Dept. of Indre).

7. Oxfordian, divisible into (*a*) Callovian, with zones of *Amm. macrocephalus*, and *A. anceps*, and (*b*) Oxfordian, with zones *A. Lamberti*, *A. Mariæ*, *A. cordatus*. This stage is well exposed on the coast of Calvados, between Trouville and Dives, where it attains a thickness of 330 feet, and is divisible into a lower sub-group of marls (Dives) with *Amm. Lamberti*, a middle sub-group of clays (Villiers) with *A. Mariæ*, and an upper sub-group of clays with *A. cordatus*. It is likewise displayed in the Boulonnais. North-eastwards, in the Ardennes, the Callovian sub-stage appears as a pyritous clay (25-30 feet) with oolitic limonite, the Oxfordian as a series of clays, marls, argillaceous sandstone (full of gelatinous silica and locally known as *gaize*) and oolitic ironstone. In the Côte-d'Or, the fossils of the Callovian and Oxfordian beds are mingled in the same strata. Round Poitiers, the Callovian division is upwards of 100 feet thick. Eastwards it dwindles down towards the Jura, but is recognisable there under the Oxfordian pyritous marls (330 feet).
6. Bathonian (Grande Oolithe) may be divided into a lower sub-stage (Vesulian) with the zone of *Ostrea acuminata* and *Amm. ferrugineus*, and an upper (Bradfordien) with the zones of *Rhynchonella decorata* and *Waldheimia digona* (*Amm. aspidoides*). In Normandy, it consists of (*a*) a lower group of strata which at one part are the Port-en-Bessin marls (100 feet or more) and at another, the famous Caen stone, so long used as a building material, and which from its saurian and other remains may be paralleled with the Stonesfield Slate; (*b*) granular limestone (Ranville), bryozoan limestone, with some of the fossils of the Bradford Clay. In the Ardennes, the Fuller's Earth is represented by some sandy limestones, lumachelles, and granular limestone, with *Ostrea acuminata*, *Amm. Parkinsoni*, *Belemnites giganteus*, &c.; the Great Oolite by a massive limestone (160-200 feet) with *Cardium pes-bovis*, *Purpura minax*, followed by 150-180 feet of limestones, with numerous fossils (*Rhynchonella decorata*, *R. elegantula*, *Ostrea flabelloides*, &c.) The limestones are replaced eastwards by marly and sandy beds. In the Côte-d'Or, the stage is largely developed, and is divided into three sub-stages: (*a*) Lower (115 feet), limestones and marls with zones of *Homomya gibbosa*, *Terebratula Mandelslohi*, *Pholadomya bucardium*; (*b*) Middle (196 feet), white limestones and oolites with zone of *Amm. arbustigerus*, *Purpura glabra* and echinoderms; (*c*) Upper (82 feet), limestones and marls with *Eudesia cardium*, *Waldheimia digona*, *Pernostrea Pellati*, *Pentacrinus Buvignieri*, and with land-plants in one of the zones.[1]
5. Bajocian (Oolithe Inférieure) is well developed in the department of Calvados, the name of the stage being taken from Bayeux. Its thickness is 60-80 feet, and it consists of: 1, Lower limestone (*Amm. Murchisonæ*); 2, limestone with numerous ferruginous oolites, fossils abundant and well preserved (*Amm. humphriesianus*, *A. Sowerbyi*, *A. Parkinsoni*, &c.); 3, Upper white oolite with abundant brachiopods, sponges and urchins (*Amm. Parkinsoni*, *Terebratula Phillipsi*, *Stomechinus bigranularis*, &c.) In the French Ardennes, the stage presents a lower group of marls (32 feet) with *Amm. Murchisonæ*, *A. Sowerbyi*, &c., followed by an upper limestone (30-130 feet) with *Amm. Blagdeni*, *A. subradiatus*, *Belem. giganteus*, &c. Towards Lorraine, this limestone becomes charged with corals, some parts being true reefs. North of Metz, the stage is mostly limestone, and reaches a thickness of 330 feet. In Burgundy, the stage is chiefly a crinoidal limestone (100 feet), capping boldly the Liassic marls. In the Jura, it attains a thickness of upwards of 300 feet, and consists chiefly of limestone. In Southern France, it swells out to great proportions, reaching in Provence a thickness of 950 feet, where it consists of the following assises in ascending order: 1, *Amm. Murchisonæ*; 2, *A. Sauzei*; 3, *A. humphriesianus*; 4, *A. niortensis*.
4. Toarcian (from Thouars = Upper Lias). In Lorraine, this stage (330-370 feet thick) consists of a lower series of marls followed by sandstone and an oolitic brown ironstone containing *Ammonites opalinus*, *A. insignis*, *Belemnites abbre-*

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[1] For a study of the gasteropods of this zone in France see M. Cossmann, *Mem. Géol. Soc. France* (3), tome iii. No. 3 (1885).

viatus. This ironstone is traceable from the Ardèche to Luxembourg. In the Ardennes, the stage includes a lower series of marls and clays (300 feet) with *Amm. serpentinus*, a middle marl containing *Amm. radians*, *A. bifrons*, and an upper limonite (Longwy) with *Amm. opalinus*, *Ostrea ferruginea*, *Trigonia navis.* In Yonne and Côte-d'Or, it consists of the following members in ascending order: 1, marls with *Posidonia* and lumachelle with *Amm. serpentinus* (15-30 feet); 2, marls with *A. complanatus* (26 feet); 3, marls with *Turbo subduplicatus* (12-20 feet); 4, blue marls with *Cancellophycus liassicus* (25-30 feet). Near St. Amand, Cher, the stage consists of nearly 200 feet of marls and clays with seven recognisable zones. In the Haute Marne, it is nearly as thick. In the Rhone basin, it consists of a lower group of limestones with *Pecten æquivalvis*, and an upper group of ferruginous beds, including an important seam of oolitic ironstone, and containing the zones of *Amm. bifrons* and *A. opalinus.* In Provence, it reaches a thickness of 950 feet, and in this region the whole Liassic subdivisions attain the great depth of 2300 feet. In Normandy, the Toarcian stage is only about 20 feet thick, but shows the characteristic ammonite zones.

3. **Liassian** (= Middle Lias and Lower Lias, in part). In Lorraine, where this stage reaches a thickness of 230 to 260 feet it consists of the following three assises in ascending order: 1, limestones (*Ammonites Davœi*) and marls; 2, marls (*A. margaritatus*); 3, sandstones (*Gryphæa regularis*). In the French Ardennes, it is 360 feet thick, and comprises: 1, sandy clay with *Amm. planicosta*, *Gryphæa regularis*, *Plicatula spinosa*; 2, marl with *Belemnites clavatus*, *Amm. capricornus*; 3, ferruginous limestone with *Amm. spinatus*, *Bel. paxillosus.* Westwards this stage becomes almost wholly marly. In Yonne and Côte-d'Or, it is divisible into three assises, in the following ascending order: 1, Belemnite limestone of Venarey (40 feet), comprising the zones of (*a*) *Amm. Valdani*, (*b*) *A. venarensis*, (*c*) *A. Henleyi*, (*d*) *A. Davœi*; 2, micaceous and pyritous marls, about 200 feet; 3, nodular limestone with large gryphites, comprising the zones of (*a*) *Amm. zetes*, (*b*) *Pecten æquivalvis*, (*c*) *Amm. acanthus.* Near St. Amand, Cher, the stage consists of nearly 300 feet of marls and marly limestone with the zones of (*a*) *Gryphæa regularis*, (*b*) *Amm. raricostatus*, (*c*) *A. ibex*, (*d*) *A. Davœi*, (*e*) *A. margaritatus*, (*f*) *A. spinatus.* In the Rhone basin, it varies up to 340 feet in thickness, but in Provence, it expands to nearly 900 feet, the lower half composed chiefly of limestones and the upper half of marls. In Normandy, it is chiefly belemnite limestone, 50 to 65 feet thick.
2. **Sinemurian** (= Lower Lias). This stage (Lias à gryphées arquées) is typically developed at Semur, Côte-d'Or (whence its name), where it consists of nodular gryphite limestone with marly bands (23-26 feet), and is divisible into three zones, which, counting from below, are marked respectively by: 1, *Ammonites rotiformis*; 2, *A. Bucklandi*; 3, *A. stellaris.* Near St. Amand, Cher, it is composed of about 15 feet of marly limestone, which represent only its upper part. In the Haute Marne and Jura, it is a limestone with curved gryphites, and ranges from 15 to 25 feet in thickness. In the basin of the Rhone it is a calcareous formation, 20 to 25 feet thick, containing the zones of *Ammonites Davidsoni*, *A. stellaris*, *A. oxynotus*, and *A. planicosta.* Farther south, it swells out in Provence to 275 feet, and is separable into a lower group with *Amm. Bucklandi*, and a higher with *Belemnites acutus*, *Amm. bisulcatus.* In Normandy, it is about 100 feet thick, and comprises clays and marly gryphite limestones (*Ammonites bisulcatus*), surmounted by gryphite limestones and clays (*Belemnites brevis*, *Waldheimia cor.*)
1. **Hettangian** (= Infra-Lias), marly and shelly limestones with *Ammonites planorbis*, &c. (corresponding to the Angulatus and Planorbis zones at the base of the Lias), resting conformably on the sandstones, marls, and bone-bed of the *Avicula contorta* zone or Rhætic group. In Lorraine, this stage is only 13 feet thick. In Luxembourg, the lower or Planorbis zone is composed of dark clays alternating with bands of fetid limestone (10-40 feet). The upper or Angulatus zone, consisting mostly of sandstone (200 feet), is well seen at Hettange, whence the name. This zone becomes less sandy as it advances into Belgium, where it forms the Marne de Jamoigne. The Hettangian stage of Burgundy is thin, and is composed of a lower Lumachelle de Bourgogne (*Ostrea irregularis*, *Cardinia Listeri*, *Ammonites Burgundiæ*) and an upper marly limestone known as "Foie de Veau" (*Ammonites Burgundiæ*, *A. moreanus*). In the basin of the Rhone, the Planorbis zone is about 40 feet thick, and the Angulatus zone 20 to 26 feet. In Cotentin, the stage is divisible into a lower sub-group of marls (*Mytilus minutus*, *Corbula*

Ludovicæ) and an upper sub-group of limestones (*Cardinia concinna, Pecten valoniensis*).

One of the most interesting features of the Lias in the northern or Jura part of Switzerland is the insect-beds at Schambelen in the Canton Aargau. The insects are better preserved and much more varied than in the English Lias, and include representatives of Orthoptera, Neuroptera, Coleoptera (upwards of 100 species of beetles), Hymenoptera, and Hemiptera. About half of the beetles are wood-eating kinds, so that there must have been abundant woodlands on the Swiss dry land in Liassic time.[1]

Germany.—In north-western Germany the subjoined classification of the Jurassic system has been adopted:[2]—

Upper or White Jura[2] (Malm).		Purbeck group (Serpulit, a limestone 160 feet thick, and Münder Mergel, a series of red and green marls, with dolomite and gypsum, at least 1000 feet thick), forming a transition between the Purbeck and Portland groups. Eimbeckhäuser Plattenkalke and zone of *Amm. gigas*, equivalent to the English Portland group (*Corbula, Modiola, Paludina, Cyrena*). Kimeridge group, Upper, with *Exogyra virgula* = Virgulian; Middle or *Pterocera* beds (Pterocerian); Lower (Astartian, Upper Sequanian), with *Nerinæa* beds and zone of *Terebratula humeralis*.[3] Corallian, with *Cidaris florigemma*, corals, *Pecten varians, Ostrea rastellaris, Nerinæa visurgis*. Oxfordian, with *Gryphæa dilatata, Amm. perarmatus, A. cordatus*. Clays with *Amm. ornatus, A. Jason, A. Lamberti, A. anceps, A. athleta* = "Ornatus clays." This stage is usually included by German geologists in the Middle Jura.
Middle or Brown Jura (Dogger).	Upper 20–100 ft.	Clays, shales, and ferruginous oolite with at the top the zone of *Amm.* (*Macrocephalites*) *macrocephalus*, equivalent to the Callovian or Kellaways rock, and at the bottom that of *Amm. Parkinsoni*.
	Middle 50 ft.	"Bifurcatus-schichten" with *Amm.* (*Cosmoceras*) *bifurcatus*. These "Bifurcatus beds," with the Hauptrogenstein above them, including the zones of *Oppellia fusca* and *O. aspidoides*, form the Bathonian stage.[4] "Coronatus-schichten," clays with *Amm.* (*Stephanoceras*) *humphriesianus, A. Blagdeni, A. Braikenridgei*, and many corals of the genera *Montlivaltia, Thecosmilia, Cladophyllia, Isastræa, Confusastræa*, and *Thamnastræa*.[5] Ostrea limestone with *Ostrea Marshi, O. eduliformis, Trigonia costata*. Clays with *Belemnites giganteus*.
	Lower up to 500 ft.	Shales, sandstones, and ironstones, with *Inoceramus polyplocus, Amm.* (*Harpoceras*) *Murchisonæ, Pecten personatus*. Clays and shales with *Amm.* (*Harpoceras*) *opalinus, A. torulosus, Trigonia navis*.

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[1] Heer, 'Urwelt der Schweiz,' p. 82.

[2] Heinr. Credner, *Ober. Jura in N. W. Deutschland*, 1863. See also the works of Oppel and Quenstedt quoted on p. 897, and K. von Seebach's *Der Hannoversche Jura*, 1864. Brauns' *Unter. Mittl. und Ober. Jura*, 1869, 1871, 1874. O. Fraas, 'Geognostische Beschreibung von Württemberg, Baden und Hohenzollern,' Stuttgart, 1882; Th. Engel, 'Geognostischer Wegweiser durch Wurttemberg,' Stuttgart (1883).

[3] Struckmann, *N. Jahrb.* 1881 (ii.) p. 102.

[4] For an account of the fauna of this stage in the upper Rhenish lowland see A. O. Schlippe, *Abhand. Geol. Specialkart. Elsass-Lothr.* IV. Heft iv. (1888).

[5] G. Meyer, 'Korallen des Doggers,' *Abhand. Geol. Specialkart. Elsass-Lothr.* IV. Heft v. (1888).

Lower or Black Jura (Lias).	Upper 30 ft.	Grey marls with *Amm.* (*Lytoceras*) *jurensis* (Jurensis-Mergel), *A.* (*Harpoceras*) *radians*.
		Bituminous shales (Posidonien-Schiefer) with *Amm. lythensis*, *A. communis*, *A. bifrons*, *Posidonia Bronni*.
	Middle 80–100 ft.	Clays with *Amm. spinatus*, *A.* (*Amaltheus*) *margaritatus*, *Belemnites paxillosus*.
		Marls and limestones with *Amm. capricornus*, *A. Davœi*.
		Dark clays and ferruginous marls with *A. brevispina*, *A. Jasoni*, *A. ibex*, *A. Jamesoni*, *Terebratula numismalis*.
	Lower 100–115 ft.[1]	Clays with *Amm. obtusus* (*Turneri*), *A. oxynotus*, *A. raricostatus* (Oxynotenlager).
		Oil shales and Pentacrinus beds resting on gryphite limestone with *Amm.* (*Arietites*) *Bucklandi*, *A. Conybeari*, *Gryphæa arcuata*, *Lima gigantea*, *Spiriferina Walcotti* (Arietenschichten).
		Sandstones with *Amm. angulatus* (Angulatenschichten), *Cardinia Listeri*.
		Dark clays, sandy layers, and limestone with *Amm. planorbis* (*psilonotus*) (Psilonotenkalk).

In lithological characters the German Lower or Black Jura presents many points of resemblance to the English Lias. Some of the shales in the upper division are so bituminous as to be workable for mineral oil. With the general succession of organisms also, so well worked out by Oppel, Quenstedt, and others, the English Lias has been found to agree closely.

The Dogger or Brown Jura represents the Lower Oolite of England and the Étages Bajocien and Bathonien of France. Its lower division consists mainly of dark clays and shales, passing up in Swabia into brown and yellow sandstones with oolitic ironstone.[2] The central group in northern Germany differs from the corresponding beds in England, France, and southern Germany by the great preponderance of dark clays and ironstone nodules. The upper group consists essentially of clays and shales with bands of oolitic ironstone, thus presenting a great difference to the massive calcareous formation on the same platform in England and France.

The Malm, or Upper or White Jura corresponds to the Middle and Upper Oolites of England, from the base of the Oxford clay upwards, with the equivalent formations in France. It is upwards of 1000 feet thick, and derives its name from the white or light colour of its rocks contrasted with the dark tints of the Jurassic strata below. It consists mainly of white limestones in many varieties; other materials are dolomite and calcareous marl. Its lower (Oxfordian) group is essentially calcareous, but with some of the fossils which occur in the Oxford clay, *e.g.* *Ammonites ornatus* and *Gryphæa dilatata*. The massive limestones with *Cidaris florigemma* are the equivalents of the Corallian. The Kimeridge group presents at its base beds equivalent to part of the Sequanian or Astartian sub-stage of France (*Astarte supracorallina*, *Natica globosa*, &c.), with such an abundance and variety of the gasteropod genus *Nerinæa* that the beds have been named the "Nerineen-Schichten." Above these come strata with *Pterocera Oceani* (Pterocerian), marking the central zone of the Kimeridgian stage. Higher still lie compact and oolitic limestones with *Exogyra virgula* (Virgulian). At the top some limestones and marly clays yield *Ammonites giganteus* (Portlandian). The most important member of the German Kimeridgian stage is undoubtedly the limestone long quarried for lithographic stone at Solenhofen, near Munich. Its excessive fineness of grain has enabled it to preserve in the most marvellous perfection the remains of a remarkably varied and abundant fauna both of the sea and land. Besides skeletons of fishes (*Aspidorhynchus*, *Lepidotus*, *Megalurus*), cephalopods showing casts of their soft parts, crabs with every part of the integument in place, and other denizens of the water, there lie the relics of a terrestrial fauna washed or blown into the neighbouring shallow lagoons—dragon-flies with the lace-work of their wings, and other insects; the entire skeletons of Pterodactyle and Rhamphorhynchus, in one case with the wing membrane preserved (Figs. 399, 400, 401), and the remains of the earliest known bird, *Archæopteryx* (pp. 893, 894). The upper Jurassic series is well developed in Hanover, where it has been carefully studied by C. Struckmann. The Portland group has been shown by him to contain eighty-five species of fossils, one-half of which are lamellibranchs, and to include the characteristic ammonites *A. gigas*, *portlandicus*, *Gravesianus*, *giganteus*.[1] The German Purbeck group attains an enormous development in Westphalia (1650 feet), where, between limestones full of *Corbula*, *Paludina*, and *Cyclas*, pointing to fresh-water deposition, there occur beds of gypsum and rock-salt.

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[1] For an account of this stage see J. A. Stuber, *Abhandl. Geol. Specialkart. Elsass-Lothr.* V. ii. (1893).

[2] For a detailed stratigraphical and palæontological account of the Lower Dogger of German Lorraine see W. Branco, *Abhand. Geol. Specialkart. Elsass-Lothr.* II. Heft ii. (1879).

Alps.—The Jurassic system in the Alps is developed under a different aspect from its varied characters in central and western Europe. It there includes massive reddish limestones or marbles like those of the Trias of the same region. Indeed it would seem that the pelagic conditions under which the Triassic limestones were deposited had not entirely passed away when the Jurassic formations came to be laid down. The Lias is well represented in the Alps under several distinct types. At the western end of the chain in the region north and south of Briançon it consists of crystalline, often brecciated limestones generally full of lamellibranchs, sometimes of corals. In Dauphiné it is made up of marly non-crystalline limestones distinguished by the number of their ammonites and belemnites, and sometimes reaching, according to Lory, a thickness of more than 6000 feet. Southwards in Provence the limestones are especially rich in brachiopods and crinoids.[2] In the Tyrol and eastern Alps the Lias presents still other lithological and palæontological characters. A distinguishing feature is the prominence of red and variegated marbles, also the abundance of genera of ammonites which are for the most part feebly represented in central and western Europe, some of the conspicuous forms being species of *Phylloceras*, *Lytoceras*, *Amaltheus*, *Oxynoticeras*, *Arietites*, *Psiloceras*, and *Schlotheimia*. At Adneth, in Salzburg, this facies has been long studied. In the Hierlatz Mountains of the Salzkammergut the Lias is represented by massive white and pink limestones with abundant brachiopods. Yet with these calcareous deposits there are also developed along the southern borders of Bohemia and eastwards in Hungary, sandy and argillaceous strata containing so much vegetation as to afford in some places beds of coal.[3] The Alpine Lias, in spite of these variations of character and organic contents, shows here and there some of the distinctive ammonite zones, so that it can be placed in comparison with that of the rest of Europe. It lies conformably on and passes down into the Rhætic series.

The equivalents of the English Lower Oolites or "Middle Jura" of the Continent have been detected in both the western and eastern Alps, but are not well developed there. In the west, where they are about 1300 feet thick, they consist of limestones, shales, and clays with calcareous nodules, which form regular alternations. Ammonites, especially of the genera *Phylloceras* and *Lytoceras*, abound, together with *Posidonia*. The zones of *Amm.* (*Harpoceras*) *Murchisonæ*, *A.* (*Harpoceras*) *concavus*, *A.* (*Son-*

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[1] 'Der Obere Jura der Umgegend von Hanover,' 1878; *Palæontolog. Abhand.* (Dames u. Kayzer) I. i. (1882); *Zeitsch. Deutsch. Geol. Ges.* 1887, p. 32.

[2] Haug, 'Les Chaines subalpines,' *Bull. Carte Géol. France*, No. 21 (1891): Lory, *Bull. Soc. Géol. France* (3), ix.

[3] Neumayr, *Abhand. k. k. Geol. Reichsanst.* 1879.

ninia) *Sowerbyi*, *A.* (*Sonninia*) *Romani*, *A. humphriesianus* (*Cœloceras subcoronatum*), *A.* (*Parkinsonia*) *Parkinsoni*, and *A.* (*Oppellia*) *fuscus* have been recognised.[1]

The Oxfordian and Corallian divisions of the Jurassic system, or Callovian, Oxfordian, and Sequanian formations are in general feebly represented in the Alpine region; but the Upper Oolites or Kimeridgian and Portlandian series attain a large development. It is this higher part of the system which in the Alps specially presents the Tithonian facies already referred to. Above the zone of *Ammonites* (*Oppellia*) *tenuilobatus* (*Aspidoceras acanthicum*) comes a mass of strata consisting of a lower group of reddish well-bedded limestones so full of *Terebratula diphya* (*janitor*) as to be named the "Diphya-limestone"; and of an upper thick-bedded or massive light-coloured limestone (Stramberg limestone, from Stramberg in Moravia). The limestones are often crowded with cephalopods, of which a large number of species, many of them peculiar, have been noticed (*Amm.* (*Phylloceras*) *ptychoicus*, *A. volanensis*, *A. hybonotus*, *A. transitorius*, *A. lithographicus*, *A. steraspis*). The presence of some of these in the Portlandian rocks of Germany serves to place all these Alpine limestones at the very top of the Jurassic system. About a dozen species of fossils pass up from them into the Cretaceous rocks. The shales or impure shaly limestones are sometimes full of the curious cephalopod-appendages known as *Aptychus* (Aptychus-beds). Some of the more massive limestones are true coral-reefs. Many of the limestone escarpments of the Alps (Hochgebirgskalk) are referable to the *Terebratula diphya* beds. In some places they are overlain by the Diphyoides-beds (with *Terebratula diphyoides*), elsewhere they pass insensibly upwards into the so-called *Biancone*—a white compact siliceous limestone containing Cretaceous cephalopods. The Diphya-limestone, with its peculiar fossils, appears to range from the Carpathians through the Alps and Apennines (where it occurs as a marble) into Sicily.[2]

Sweden.—The coal-bearing Rhætic series developed in Scania and referred to on p. 870, is followed by a series of marine strata, in which a number of the ammonite-zones of the Lower and Middle Lias have been recognised as high as that of *Amm. margaritatus*.[3] Similar strata are found on the island of Bornholm. These Scandinavian deposits and those in the north of Scotland mark the northern and western limits of the Jurassic system in Europe.

Russia.—Jurassic formations spread over a larger area in Russia than in any other part of Europe, for they sweep northwards over a vast breadth of territory to the White Sea, and extend eastwards into Asia. Yet in this wide area it is only the upper half of the system which appears. The Lias and the stages below the Callovian are absent. The fauna of these Russian Jurassic formations is so peculiar, and for a long time yielded so few species found elsewhere in Europe, that it was difficult to correlate these rocks with those of better known regions. More sedulous research, however, has now in large measure removed this difficulty, and shown that some of the recognised life-zones of western Europe can be detected in Russia.[4] At the bottom lies (1) the Callovian stage, consisting of clays, divided into—*a*. Lower with *Amm.* (*Cosmoceras*)

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[1] Haug, *Bull. Cart. Géol. France*, No. 21 (1891).

[2] In the voluminous literature of this subject the following works may be consulted: Oppel, *Z. Deutsch. Geol. Ges.* xvii. (1865) 535; Neumayr, *Abhandl. Geol. Reichsanstalt*, v.; Zittel, *Paläont. Mittheil. Mus. Bayer.*; Hébert, *Bull. Soc. Géol. France*, ii. (2) p. 148, xi. (3) p. 400; E. W. Benecke, 'Trias und Jura in den Südalpen,' 1866; 'Geognostisch. Paläontologische Beiträge,' 8vo, Munich, 1868; C. Moesch, 'Jura in den Alpen, Ostschweiz,' 1872; E. Fraas, 'Scenerie der Alpen.' See also the 'Jura-studien,' &c. of Neumayr, already cited (p. 895), and the papers of Favre, Loriol, Renevier, and others.

[3] J. C. Moberg, *Sverig. Geol. Undersökn.* Stockholm, 1888.

[4] Neumayr, *Geogn. Palaeontol. Beiträge*, 1876, vol. ii.; Nikitin, *Neues Jahrb.* 1886, ii. p. 205; *Mém. Acad. St. Pétersbourg*, 1881; Pavlow, *Bull. Soc. Géol. France*, xii. (1884); *Bull. Soc. Nat. Moscou*, 1889, 1891.

calloviensis, *A. gowerianus*; *b.* Middle with *Amm.* (*Cosmoceras*) *Jason*, *A.* (*Stephanoceras*) *coronatus*; *c.* Upper with *Amm.* (*Quenstedticeras*) *Lamberti*, *A.* (*Cosmoceras*) *Duncani.* (2) Oxfordian, composed of dark sandy clays and divided into—*a.* Lower with *Amm.* (*Cardioceras*) *cordatus*, *A.* (*Card.*) *vertebralis*, *A.* (*Perisphinctes*) *plicatilis*, *A.* (*Aspidoceras*) *perarmatus*; *b.* Upper with *Amm.* (*Cardioceras*) *alternans*, *A.* (*Perisphinctes*) *Martelli.* (3) Volgian, consisting of green, brown, and dark sandstones and sands. The lower part of this group contains *Amm.* (*Perisphinctes*) *virgatus*, *A.* (*Perisph.*) *Pallasi*, *Belemnites absolutus*, *B. magnificus*, *Aucella Pallasi*, *A. mosquensis*, and the higher part yields *Belemnites mosquensis*, *Holcostephanus Blakei*, and many species of the lamellibranch *Aucella.* The group is correlated by Pavlow with the Portlandian stage of western Europe. At the top a number of species pass up into the Neocomian series.[1]

North America.—So far as yet known, rocks of Jurassic age play but a subordinate part in North American geology. Perhaps some of the red strata of the Trias belong to this division, for it is difficult, owing to paucity of fossil evidence, to draw a satisfactory line between the two systems. Strata containing fossils believed to represent those of the European Jurassic series have been met with in recent years during the explorations in the western domains of the United States. They occur among some of the eastern ranges of the Rocky Mountains (Colorado; Black Hills, Dakota; Wind River Mountains; Uinta Mountains; Wahsatch range, &c.), as well as in the Sierra Nevada, California, and other localities on the western side of the watershed. They have been recognised far to the north, beyond the great region of Azoic and Palæozoic rocks, in the Arctic portion of the continent. They have been met with also in South America, where they appear to range far southwards into the Argentine Republic.[2] The fossils include species of *Pentacrinus*, *Monotis*, *Gryphæa*, *Trigonia*, *Lima*, *Ammonites* (*Amaltheus*, *Arietites*, *Cardioceras*), and *Belemnites.*

The American Jurassic rocks, though a few European species appear to occur in them, have not yet been satisfactorily correlated with the subdivisions of the system in Europe. The younger members of the series are probably best developed. In these strata as exposed in Wyoming, Utah, Dakota, and Colorado great discoveries of vertebrate remains have been made. Professor Marsh has brought to light from the upper Jurassic strata of Colorado the remarkable series of reptilian forms already referred to which have given a wholly new interest and importance to the Jurassic rocks of America. Among remains of fish (*Ceratodus*), tortoises, pterodactyles, and crocodilians, he has recognised the bones of herbivorous deinosaurs (*Atlantosaurus*, *Brontosaurus*, *Stegosaurus*, *Morosaurus*, *Apatosaurus*), together with the carnivorous *Creosaurus* and the curious ostrich-like *Laosaurus.* With this rich and striking reptilian fauna are associated the remains of many genera of small mammals which have been named by Professor Marsh *Allodon*, *Ctenacodon*, *Dryolestes*, *Stylacodon*, *Asthenodon*, *Laodon*, *Diplocynodon*, *Docodon* [*Enneodon*], *Menacodon*, *Tinodon*, *Triconodon*, *Priacodon*, *Paurodon.*[3]

Asia.—In India, as already stated, the upper part of the enormous Gondwána system is possibly referable to the Jurassic period. In Cutch, however, a marine series of strata occurs containing a representation of the European Jurassic system from the Inferior Oolite up to the Portland group inclusive. These rocks attain a thickness of 6300 feet, of which the lower half is chiefly marine and the upper mainly fresh-water. Among the zones recognised by Stoliczka were those of *Ammonites macrocephalus*, *A. anceps*, and *A. athleta* of the Kellaways (Callovian) group; *A. Lamberti*, *A. cordatus*, *A. transversarius* of the Oxford clay; *A. tenuilobatus* of the Kimeridge group.[4]

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[1] Pavlow, *Bull. Soc. Nat. Moscou*, 1891.

[2] O. Behrendsen has found Lower and Middle Lias, and higher Jurassic beds on the eastern slopes of the Argentine Cordilleras. *Zeit. Deutsch. Geol. Gesell.* xliii. 369 (1891).

[3] Marsh, *Amer. Journ. Sci.* xv. (1878) p. 459; xviii. (1879) pp. 60, 215, 396; xx. (1880) p. 235; xxi. (1881) p. 511; xxxiii. (1887) p. 237; *Geol. Mag.* (1887) pp. 241, 289.

[4] Medlicott and Blanford's 'Geology of India,' p. 253. Waagen, *Palæont. Indica*, 1875.

Australasia.—The existence of Jurassic rocks in Queensland and western Australia has been demonstrated by the discovery of recognisable Jurassic species and others closely allied to known Jurassic forms.[1] In Queensland above the Permo-Carboniferous rocks comes the Burrum formation, a great series of coal-bearing rocks, with *Sphenopteris*, *Thinnfeldia*, *Alethopteris*, *Tæniopteris*, *Podozamites*, *Otozamites*, *Baiera*, and a few animal remains, including species of *Corbicula* and *Rocellaria*. This group is followed by another sandy and conglomeratic series with abundant remains of land-plants and workable coals, forming the valuable Ipswich formation. From these strata a large flora has been collected, together with cyprids, coleoptera, and Unio. From the plant-remains these two formations have been grouped as Jura-Trias.[2] Traces of Jurassic rocks have been found in New Caledonia and the northern end of New Guinea.

In New Zealand a thick series of rocks classed as Jurassic is subdivided as follows:—

Mataura series, estuarine, with terrestrial plants (8 species known).
Putakaka series, marlstones and sandstones passing into conglomerates, and enclosing plant-remains and irregular seams of coal; marine fossils (11 species known) of Middle Oolite facies.
Flag Hill series, with species of *Rhynchonella*, *Terebratula*, *Spiriferina*, &c.
Catlin's River and Bastion series, consisting in the upper part of conglomerates and grits, with obscure plant-remains, and in the lower part of sandstones. Fossils abundant (especially ammonites), and affording means for defining horizons. This division is referred to the Lias.[3]

Section iii. Cretaceous.

The next great series of geological formations received the name of Cretaceous system, from the fact that, in north-western Europe, one of its most important members is a thick band of white chalk (*creta*). It presents very considerable lithological and palæontological differences as it is traced over the world. In particular, the white chalk is almost wholly confined to the Anglo-Parisian basin where the system was first studied. Probably no contemporaneous group of rocks presents more remarkable local differences than the Cretaceous system of Europe. These differences are the records of an increasing diversity of geographical conditions in the history of the Continent.

§ 1. General Characters.

ROCKS.—In the European area, as will be afterwards pointed out in more detail, two tolerably distinct areas of deposit can be recognised, each with its own character of sedimentary accumulations, as in the case of the Jurassic system already described. The northern tract includes Britain, the lowlands of central Europe southwards into Silesia, Bohemia, and round the Ardennes into the basin of the Seine. The southern region embraces the centre and south of France, the range of the Alps, and the basin of the Mediterranean eastwards into Asia. In the northern area, which appears to have been a basin in great measure shut off from free communication with the Atlantic, the deposits are largely of a littoral or shallow-water kind. The basement beds, usually sands or sandstones, sometimes conglomerates, are to a large extent glauconitic (greensand). The marked diffusion of glauconite, both in the sandstones and marls, is one of the distinctive characters of this series of rocks. Another feature is the abundance of soluble silica (sponge-spicules) more particularly in the formation called the Upper Greensand, and in the Lower Chalk of many parts of the south and south-east of England and the north of France. In Saxony and Bohemia, the Cretaceous system consists chiefly of massive sandstones, which appear to have accumulated in a gulf along the southern margin of the northern basin. Considerable bands of clay, occurring on different platforms among the European Cretaceous rocks, are often charged with fossils, sometimes so well preserved that the pearly nacre of the shells remains, in other cases encrusted or replaced by marcasite. Alternations of soft sands, clays, and shales, usually more or less glauconitic, are of frequent occurrence in the lower parts of the system (Neocomian and older Cenomanian). The calcareous strata assume sometimes the form of soft marls, which pass into glauconitic clays, on the one hand, and into white chalk, on the other. The white chalk itself is a pulverulent limestone, mainly composed of fragmentary shells and foraminifera. Its upper part shows layers of flints, which are irregular lumps of dark-coloured, somewhat impure chalcedony, disposed for the most part along the planes of bedding, but sometimes in strings and veins across them. The flints frequently enclose silicified fossils, especially sponges, urchins, brachiopods, &c. (see pp. 141, 495). The chalk, in some places, becomes a hard dull limestone, breaking with a splintery fracture. Nodular phosphate of lime or phosphatic chalk, occurring on different horizons in the system, is extensively worked as a source of artificial manure in the Upper Chalk of Belgium.[1] It has been found also in the north of France, and at Taplow, near Maidenhead, in England.[2]

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[1] Moore, *Q. J. Geol. Soc.* xxvi. 261. W. B. Clarke, *op. cit.* xxiii. 7. R. Etheridge jun., 'Catalogue of Australian Fossils,' 1878.

[2] Jack and Etheridge, 'Geology and Palæontology of Queensland' (1892), chaps. xxiii.-xxx.

[3] Hector's 'Handbook of New Zealand,' p. 31. Compare F. W. Hutton, *Quart. Journ. Geol. Soc.* 1885, p. 204.

The terrestrial vegetation of the period has in different places been aggregated into beds of coal. These occur in north-western Germany among the Wealden deposits, where they are mined for use; also to a trifling extent in the Wealden series of England; they are likewise found in the Cenomanian series of Saxony and the Senonian of Magdeburg. The upper Cretaceous (Laramie) rocks of the Western Territories of the United States consist largely of sandstones and conglomerates, among which are numerous important seams of coal. Beds of concretionary brown iron-ore are present in the Cretaceous series of Hanover, and similar deposits were once worked in the English Wealden series. In the southern European basin, where the conditions of deposit appear to have been more those of an open sea freely communicating with the Atlantic, the most noticeable feature is the massiveness, compactness, and persistence of the limestones over a vast area. These rocks, often crowded with hippuritids, from their extent and organic contents, indicate that, during Cretaceous times, the Atlantic stretched across the south of Europe and north of Africa, far into the heart of Asia, and may not impossibly have been connected across the north of India with the Indian Ocean.

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[1] Cornet, *Quart. Journ. Geol. Soc.* xlii. p. 325; Renard et Cornet, *Bull. Acad Roy. Belg.* xxi. (1891) p. 126.

[2] A. Strahan, *Quart. Journ. Geol. Soc.* xlvii. (1891) p. 356.

LIFE.—The Cretaceous system, both in Europe and North America, presents successive platforms on which the land-vegetation of the period has been preserved, though most of the strata contain only marine organisms. This terrestrial flora possesses a great interest, for it includes the earliest known progenitors of the abundant dicotyledonous angiosperms of the present day. In Europe during the earlier part of the Cretaceous period, it appears to have closely resembled the vegetation of the previous ages, for the same genera of ferns, cycads, and conifers, which formed the Jurassic woodlands, are found in the rocks. Yet that angiosperms must have already existed is made certain by the sudden appearance of numerous forms of that class, at the base of the Upper Cretaceous formations in Saxony and Bohemia, whence forms of *Acer*, *Alnus*, *Credneria*, *Cunninghamites*, *Salix*, &c., have been obtained. Still more varied and abundant is the dicotyledonous flora preserved in the Upper Cretaceous formations in Westphalia, from which 53 species of dicotyledonous plants have been obtained, belonging to the genera *Populus*, *Myrica*, *Quercus*, *Ficus*, *Credneria*, *Viburnum*, *Aralia*, *Eucalyptus*, &c., besides algæ, ferns, cycads, conifers, and various monocotyledons (Fig. 410).[1] Another rich Cretaceous flora is found in the corresponding beds at Aix-la-Chapelle. It includes numerous ferns (*Gleichenia*, *Lygodium*, *Danæites*, *Asplenium*, *Pteridoleimma*), conifers (*Sequoia*, *Cunninghamites*), *Caulinea*, *Dryophyllum*, *Myricophyllum*, *Ficus*, *Laurophyllum*, and three or four kinds of screw-pine (*Pandanus*).[2] The prevalent forms which give so modern an aspect to this flora, and which occur also in Westphalia, are *Proteaceæ*, many of them being referred to genera still living in Australia or at the Cape of Good Hope. These interesting fragments indicate that the climate of Europe, at the close of the Cretaceous period, was doubtless greatly warmer than that which now prevails, and nourished a vegetation like that of some parts of Australia or the Cape. Further information has been afforded regarding the extension of this flora by the discovery in North Greenland of a remarkable series of fossil-plants, of which Heer has described nearly 200 species, including more than 40 kinds of ferns, with club-mosses, horsetail reeds, cycads (*Cycas*,

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[1] Hosius and Von der Marck, "Die Flora der Westfälischen Kreideformation," *Palæontographica*, xxvi. (1880) p. 125. The total flora described by these observers is made up of 85 species from the Upper and 20 species from the Lower Cretaceous beds.

[2] T. Lange, *Zeitsch. Deutsch. Geol. Ges.* 1890, p. 658 ; and H. von Dechen, as cited *postea*, p. 954.

Podozamites, *Otozamites*, *Zamites*), conifers (*Baiera*, *Ginkgo*, *Juniperus*, *Thuyites*, *Sequoia*, *Dammara*, *Pinus*, &c.), monocotyledons (*Arundo*, *Potamogeton*, &c.), and many dicotyledons, including forms of poplar, myrica, oak, fig, walnut, plane, sassafras, laurel, cinnamon, ivy, aralia, dogwood, magnolia, eucalyptus, ilex, buckthorn, cassia and others.[1]

In North America, also, abundant remains of a similar vegetation have been obtained from the Cretaceous rocks of the Western Territories. The Laramie group of strata in particular has yielded a remarkably large and varied flora. Out of more than 100 species of dicotyledonous angiosperms there found, half are related to still living American trees Among them are species of oak, willow, beech, plane, poplar, maple, hickory, fig, tulip-tree, sassafras, laurel, cinnamon, buckthorn, together with ferns, American palms (sabal, *Flabellaria*), conifers, and cycads.[2] The "Potomac formation" of Virginia and Maryland has a special interest from its age. It is referred with some probability to the Neocomian period, and it has yielded about 350 species of plants, viz. three species of Equiseta, 139 ferns, 22 cycads, and more than 100 conifers. But besides

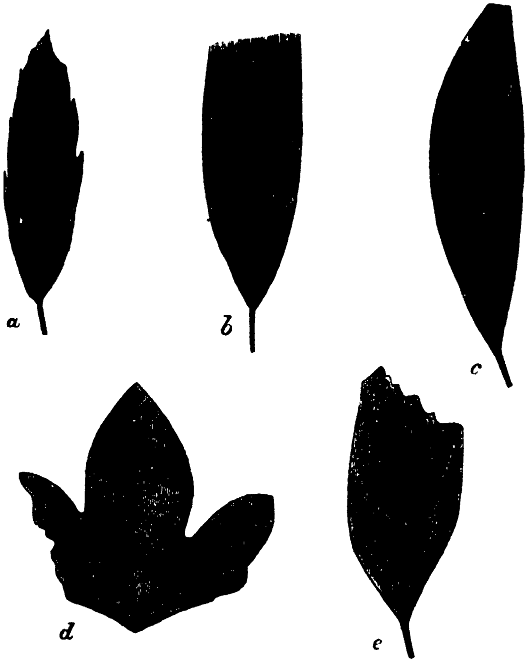

Fig. 410.—Cretaceous Plants.

a, Quercus rinkiana ($\frac{2}{3}$); *b*, Cinnamomum sezannense ($\frac{2}{3}$); c, Ficus atavina ($\frac{2}{3}$); *d*, Sassafras recurvata ($\frac{2}{3}$); *e*, Juglans arctica ($\frac{1}{2}$).

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[1] 'Flora Fossilis Arctica,' vols. vi. and vii. (1882-83).

[2] For a synopsis of the Laramie flora see L. F. Ward, *6th Ann. Rep. U.S. Geol. Surv.* 1885.

this assemblage, which is distinctly Mesozoic in character, the deposits have furnished no fewer than 29 genera and 75 species of angiosperms. Of these higher forms of vegetation about two-thirds are new, and the more peculiar forms seem to be what are known as "generalised types," indicating the great antiquity of the flora. But among the genera there are found *Sassafras*, *Ficus*, *Myrica*, *Bombax*, and *Aralia*.[1]

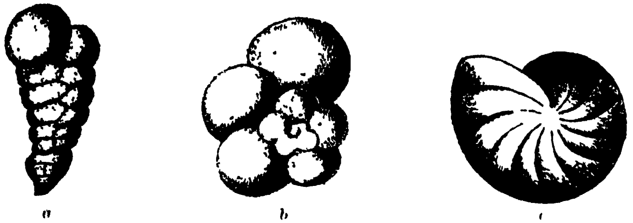

Fig. 411.—Cretaceous Foraminifera.
a, Gaudryina pupoides, D'Orb.; *b*, Globigerina cretacea, D'Orb.; *c*, Cristellaria rotulata, D'Orb. (all magnified).

The known Cretaceous **fauna** is tolerably extensive. Foraminifera now reached an importance as rock-builders which they never before attained. Their remains are abundant in the white chalk of the northern European basin, and some of the hard limestones of the southern basin are mainly composed of their aggregated shells. The glauconite grains of many of the greenish strata are the internal casts of foraminiferous shells (see pp. 456, 652). Some of the more frequent genera are *Globigerina*, *Orbitolina*, *Nodosaria*, *Textilaria*, and *Rotalia* (Fig. 411). Calcareous sponges are of frequent occurrence, while siliceous sponges must have swarmed on the floor of the Cretaceous seas, for their siliceous spicules are abundant, and entire individuals are not uncommon.[2] Characteristic genera (Fig. 412) are *Ventriculites*, *Siphonia*, *Cœloptychium*, and *Corynella*. The formation of flints has been referred to the operation of sponges. Undoubtedly these animals secreted an enormous quantity of silica from the water of the Cretaceous sea, and though

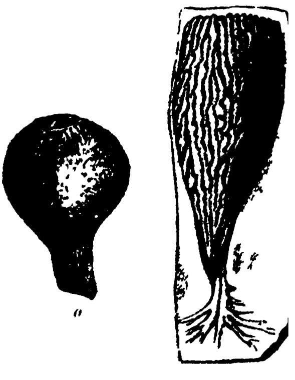

Fig. 412.—Cretaceous Sponges.
a, Siphonia pyriformis, Goldf. (½); *b*, Ventriculites decurrens, var. tenuiplicatus, Smith (½).

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[1] W. M. Fontaine, 'The Potomac or Younger Mesozoic Flora,' *Monog. U.S. Geol. Surv.* vol. xv. (1889). See also O. Feistmantel, *Zeitsch. Deutsch. Geol. Ges.* 1888, p. 27.

[2] See on Sponge spicules, papers by Prof. Sollas, *Ann. Mag. Nat. Hist.* ser. 5, vi. and memoirs by Dr. G. J. Hinde, 'Fossil Sponge Spicules,' Munich, 1880; 'Cat. of Fossil Sponges, British Museum,' 1883; *Phil. Trans.* vol. clxxvi. p. 403, 1886; 'British Fossil Sponges,' *Pal. Soc.* vol. xl. xli. 1887-88. The sponge spicules of the Upper Cretaceous rocks are very generally in the condition of amorphous or colloid silica; those of the Lower Cretaceous are frequently of crystalline silica.

the flints are certainly not due merely to their action alone, amorphous silica may have been aggregated by a process of chemical elimination round dead sponges or other organisms (p. 495). Mollusks and urchins have been completely silicified in the Chalk.

On the whole, corals are not abundant in Cretaceous deposits, though they occur plentifully in the so-called coral limestone of Faxoe. They seem to have been chiefly solitary forms, some of the more characteristic genera being *Trochocyathus*, *Caryophyllia*, *Trochosmilia*, *Parasmilia*, *Micrabacia*, and *Cyclolites*. The rugose corals so abundant among Palæozoic rocks are now doubtfully represented by the little Neocomian *Holocystis*. Sea-urchins are conspicuous among the fossils of the Cretaceous system. A few of their genera are also Jurassic, while a not inconsiderable number still live in the present ocean. One of the most striking results of recent deep-sea dredging is the discovery of so many new genera of echinoids, either identical with, or very nearly resembling, those of the Cretaceous period, and having thus an unexpectedly antique character.[1] Some of the most abundant and typical Cretaceous genera (Fig. 413) are *Ananchytes* (*Echinocorys*), *Holaster*, *Toxaster*, *Micraster*, *Hemiaster*, *Hemipneustes*, *Cardiaster*, *Pygurus*, *Echinobrissus* (*Nucleolites*), *Echinoconus* (*Galerites*), *Discoidea*, *Cyphosoma*, *Pseudodiadema*, *Salenia*, *Cidaris*. A few crinoids have been met with, of which *Bourgueticrinus* and *Marsupites* of the Upper Chalk are characteristic.

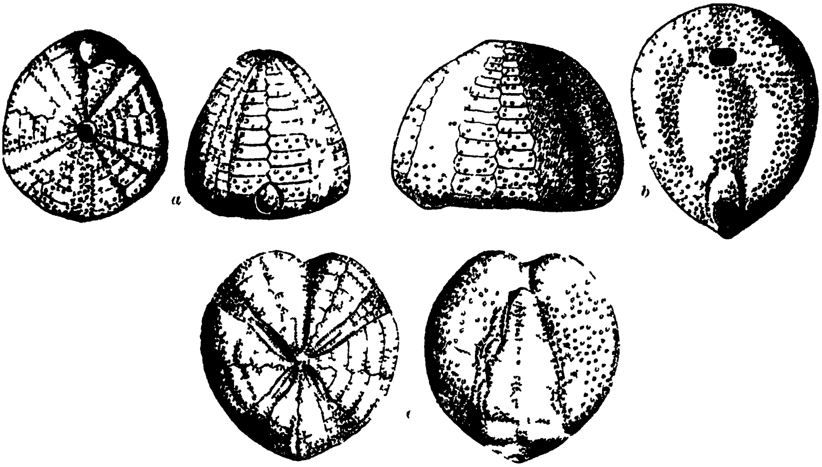

Fig. 413.—Upper Cretaceous Echinoids.
a, Echinoconus conicus, Brey. (=Galerites albo galerus Lam.) (⅔); b, Ananchytes ovatus (=Echinocorys vulgatus, Leske) (½); c, Micraster cor anguinum Klein (½).

Polyzoa abound in some parts of the system, especially in the upper formations (*Cellaria*, *Vincularia*, *Membranipora*, *Micropora*, *Retepora*). The brachiopods (Fig. 414) are abundantly represented by species of *Terebratula* and *Rhynchonella*, which approach in form to still living species.

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[1] A. Agassiz, "Report on Echinoidea," *Challenger* Expedition, vol. iii. p. 25.

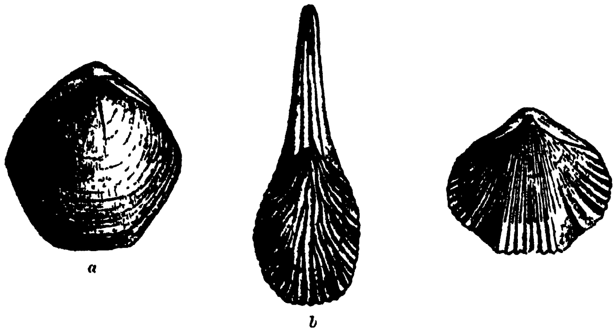

Fig. 414.—Cretaceous Brachiopods.
a, Terebratula carnea, Sow. (⅔); *b*, Terebrirostra lyra, Sow. (⅔); *c*, Rhynchonella plicatilis, var. octoplicata, Sow. (⅔).

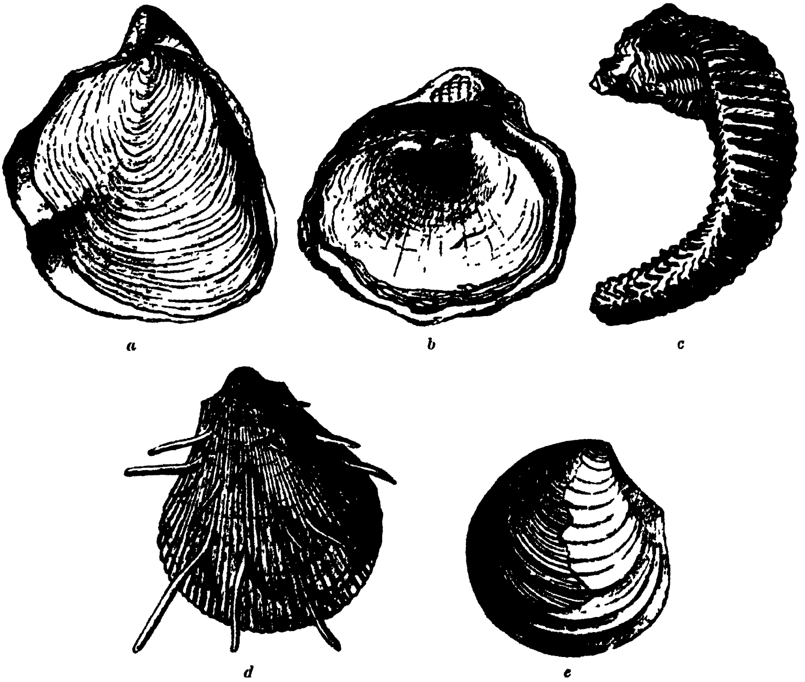

Fig. 415.—Cretaceous Lamellibranchs.
a, Exogyra (Ostrea) columba, Lam. (½); *b*, Ostrea vesicularis, Lam. (½); *c*, Ostrea carinata, Lam. (½); *d*, Spondylus (Lima) spinosus, Desh. (⅔); *e*, Inoceramus Cuvieri, Sow. (young spec.) (½).

Other contemporaneous genera were *Crania* (numerous species), *Thecidium*, *Magas*, *Terebratella*, *Lyra* (*Terebrirostra*), *Trigonosemus*, *Terebratulina*, and *Argiope*. Among the most abundant genera of lamellibranchs (Fig. 415) are *Inoceramus*, *Exogyra*, *Ostrea*, *Spondylus*, *Lima*, *Pecten*, *Perna*, *Modiola*,

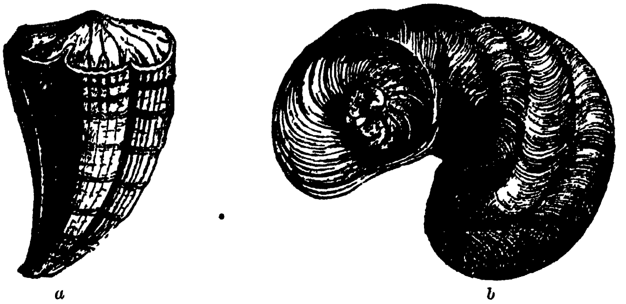

Fig. 416.—Cretaceous Lamellibranchs (Hippuritids).
a, Hippurites organisans, Desm. (nat. size); *b*, Caprotina (Requienia) ammonia, D'Orb. (⅓)

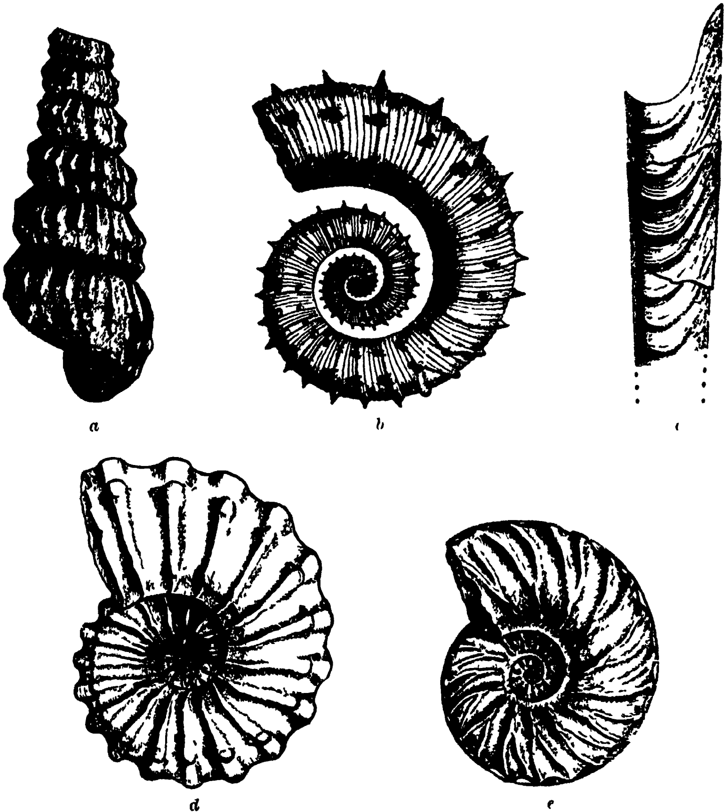

Fig. 417.—Cretaceous Cephalopods.
a, Turrilites costatus, Lam. (⅓); *b*, Crioceras Emerici, Lév. (½); *c*, Baculites anceps, Lam. (⅓); *d*, Ammonites (Acanthoceras) rothomagensis, Brong. (¼); *e*, Ammonites varians, Sow. (⅔).

Trigonia, *Isocardia*, *Cardium*, *Venus*. *Inoceramus* and *Exogyra* are specially characteristic, but still more so is the family of *Hippuritidæ* or *Rudistes.* These singular forms are entirely confined to the Cretaceous system: their most common genera (Fig. 416) being *Hippurites*, *Radiolites*, *Sphærulites*, *Caprina*, *Monopleura*, and *Caprotina* (*Requienia*).[1] Hence, according to present knowledge, the occurrence of hippuritids in a limestone suffices to indicate the Cretaceous age of the rock. The most common gasteropods belong to the genera *Actæonella*, *Turbo*, *Solarium*, *Trochus*, *Pleurotomaria*, *Cerithium*, *Rostellaria*, *Aporrhais*, *Fusus*, *Mitra*, and *Murex.* Cephalopods must have swarmed in some of the Cretaceous seas (Figs. 417, 418, 419). Their remains are abundant in the Anglo-Parisian basin and thence eastwards, but are comparatively infrequent in the southern Cretaceous area. To the geologist, they have a value similar to those of the Jurassic system, as distinct species are believed to be restricted in their range to particular horizons, which have by their means been identified from district to district. To the student of the history of life, they have a special interest, as they include the last of the great Mesozoic tribes of the Ammonites and Belemnites. These organisms continue abundant up to the top of the Cretaceous system, and then disappear from the European geological record.[2] Never was cephalopodous life so varied as in the Cretaceous period, just before its decline. It included some old Ammonite genera such as *Phylloceras*, *Lytoceras*, and *Haploceras*, some of which had continued even from Liassic time, together with new genera, some resembling old types (*Schloenbachia*), others which now appeared for the first time. Of these new forms *Crioceras* (Fig. 417) is an Ammonite with the coils of the shell not contiguous. *Scaphites* and *Ancyloceras* have the last coil straightened, and its end bent into a crozier-like shape (Fig. 418). *Toxoceras*, as its name implies, is merely bent into a bow-like form. *Hamites* is a long tapering shell, curved round hook-wise upon itself. In *Ptychoceras* the long tapering shell is bent once and the two parts are mutually adherent. *Turrilites* (Fig. 417) is a spirally coiled shell, and *Helicoceras* resembles it, but has the coils not in contact. *Baculites* (Fig. 417) is the simplest of all the forms, being a mere straight-chambered shell somewhat like the ancient *Orthoceras.* These forms, in numerous species, are almost entirely confined to the Cretaceous system, at the summit of which they disappear. The genus *Nautilus* is found not infrequently in Upper Cretaceous rocks. Another characteristic cephalopod is *Belemnitella* (Fig. 419), which occurs abundantly in the higher parts of the system. The Belemnites are more particularly characteristic of Lower Cretaceous rocks, and belong to Zittel's groups of the "Bipartiti," "Conophori," and "Dilatati."

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[1] For a study of the *Rudistes*, see the Memoir by H. Douvillé, *Mém. Soc. Géol. France* (3), i. (1890); ii. (1892).

[2] No abrupt disappearance of a whole widely-diffused fauna probably ever took place. The cessation of Ammonites with the Cretaceous system in Europe can only mean that in this area there intervened between the deposition of the Cretaceous and Tertiary strata a long interval, marked by such physical revolutions as to extirpate Ammonites from that region. That the tribe continued elsewhere to live on into Tertiary time appears to be proved by the occurrence of some Ammonite remains in the oldest Tertiary beds of California. A. Heilprin, 'Contributions to the Tertiary Geology and Palæontology of the United States,' Philadelphia, 1884, p. 102.

Vertebrate remains have been obtained in some number from the Cretaceous rocks. Fish are represented by scattered teeth, scales, or bones, sometimes by more entire skeletons. The most frequent genera are *Odontaspis*,[1] *Lamna*, *Oxyrhina*, *Ptychodus*, *Hybodus*, *Mesodon* (*Pycnodus*),

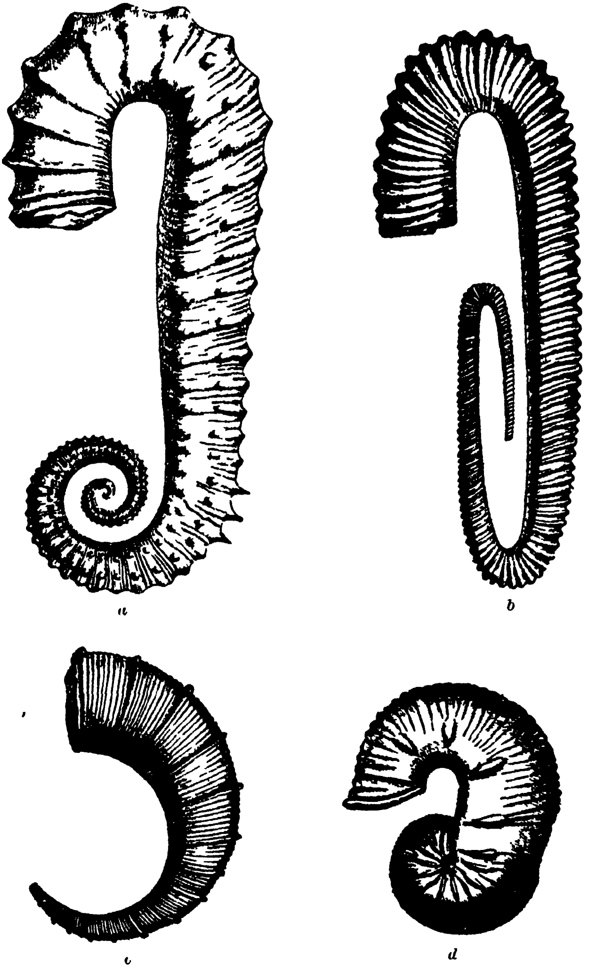

Fig 418 —Cretaceous Cephalopods.
a, Ancyloceras matheronianus, D Orb (⅛), *b*, Hamites attenuatus, Sow (½); *c*, Toxoceras bituberculatus, D Orb , *d*, Scaphites æqualis, Sow.

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[1] *Odontaspis* (*Lamna*) *elegans* ranges up to the Rupelian (Oligocene) beds. A. Rutot, *Ann. Soc. Géol. Belg.* 1875, p. 34.

Sphærodus, and the earliest of the teleostean tribes, which include the vast majority of modern fishes—*Protosphyræna*, *Cimolichthys*, *Enchodus*, *Stratodus*, *Beryx* (Fig. 420), *Syllæmus*, *Portheus*, &c.

Reptilian life has not been so abundantly preserved in the Cretaceous as in the Jurassic system, nor are the forms so varied. In the European area the remains of Chelonians of several genera (*Chelone*, *Protemys*, *Platemys*) have been recovered. The last of the tribe of deinosaurs died out towards the close of the Cretaceous period. Among the Cretaceous forms of this order are the *Megalosaurus* and *Cetiosaurus*, which survived from Jurassic time; likewise *Pelorosaurus*, *Polacanthus*, *Iguanodon*, *Hylæosaurus*, *Hypsilophodon*, *Ornithopsis*. Of these *Iguanodon* is the most familiar type (Fig. 421). Some of its teeth and bones were first found in the Wealden series of Sussex, but in recent years, almost entire skeletons have been disinterred from the ancient alluvium filling up valleys of the Cretaceous period in Belgium, so that its osteology is now well known. Like other deinosaurs, it had many affinities with birds. Palæontologists have differed in opinion as to whether it walked on all fours or erect. M. Dollo, who has had the advantage of working out the structure of the wonderfully perfect Belgium specimens, believes that the animal moved on its hind legs, which are disproportionately longer than the fore ones. Its powerful tail obviously served as an organ of propulsion in the water, and likewise to balance the creature as it walked. Its strange fore-limbs, armed with spurs on the digits, doubtless enabled it to defend itself from its carnivorous congeners; it was itself herbivorous.[1] Among Cretaceous rocks the order of Lizards is represented by *Coniasaurus*,

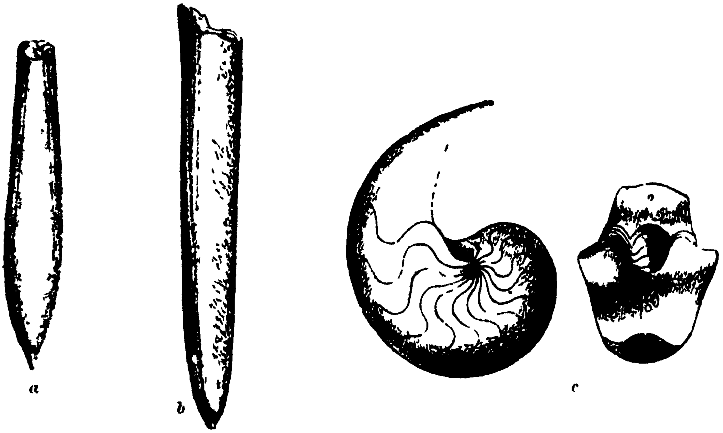

Fig. 419.—Upper Cretaceous Cephalopods.
a, Belemnitella plena Belemnites plenus), Blainv. (½); *b*, Belemnitella mucronata, Schloth. (½); *c*, Nautilus danicus, Schloth. (½).

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[1] Mantell's 'Illustrations of the Geology of Sussex,' 1827. For recent additions to our knowledge, see Dollo, *Bull. Mus. Roy. Belgique*, ii. (1883). *Ann. Sci. Géol.* xvi. (1883) No. 6.

Dolichosaurus, and *Leiodon*. The gigantic *Mosasaurus*, placed among lacertilians by Owen, but among "pythonomorphs" by Cope, is estimated to have had a length of 75 feet, and was furnished with fin-like paddles, by which it moved through the water. True crocodiles frequented the rivers of the period, for the remains of several genera have been recognised (*Goniopholis*, *Pholidosaurus*, *Theriosuchus*). The ichthyosaurs and plesiosaurs were still represented in the Cretaceous seas of Europe. The pterosaurs likewise continued to be inhabitants of the land, for the bones of several species of pterodactyle have been found. These remains are usually met with in scattered bones, only found at rare intervals and wide apart. In a few places, however, reptilian remains have been disinterred in such numbers from local deposits as to show how much more knowledge may yet be acquired from the fortunate discovery of other similar accumulations. One of the most remarkable of these exceptional deposits is the hard clay above referred to as filling up some deep valley-shaped depressions in the Carboniferous rocks near Bernissart in Belgium, and which has been unexpectedly encountered at a depth of more than 1000 feet below the surface in mining for coal. These precipitous defiles were evidently valleys in Cretaceous times, in which fine silt accumulated, and wherein carcases of the reptiles of the times were quietly covered up and preserved, together with remains of the river chelonians and fishes, as well as of the ferns that grew on the cliffs overhead. These deposits have remained undisturbed under the deep cover of later rocks.[1] Again, from the so-called "Cambridge Greensand"—a bed about 1 foot thick lying at the base of the Chalk of Cambridge, and largely worked for the phosphate of lime which is supplied by phosphatic nodules and phosphated fossils—there have been exhumed the remains of several chelonians, the great deinosaur *Acanthopholis*, several species of *Plesiosaurus*, 5 or 6 species of *Ichthyosaurus*, 10 species of *Pterodactylus*—from the size of a pigeon upwards, one of them having a spread of wing amounting to 25 feet—3 species of *Mosasaurus*, a crocodilian (*Polyptychodon*), and some others. From the same limited horizon also the bones of at least two species of birds have been obtained.

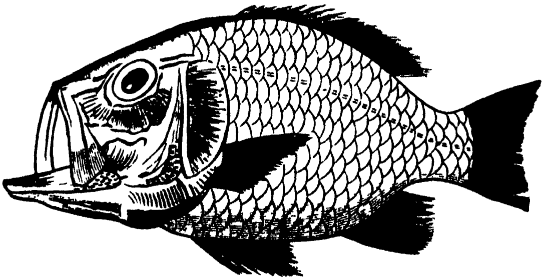

Fig. 420.—Cretaceous Fish.
Beryx lewesiensis (¼).

In recent years the most astonishing additions to our knowledge of ancient reptilian life have been made from the Cretaceous rocks of western North America, chiefly by Professors Leidy, Marsh, and Cope.[1]

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[1] E. Dupont, *Bull. Acad. Roy. Belg.* 2e sér. xlvi. (1878) p. 387.

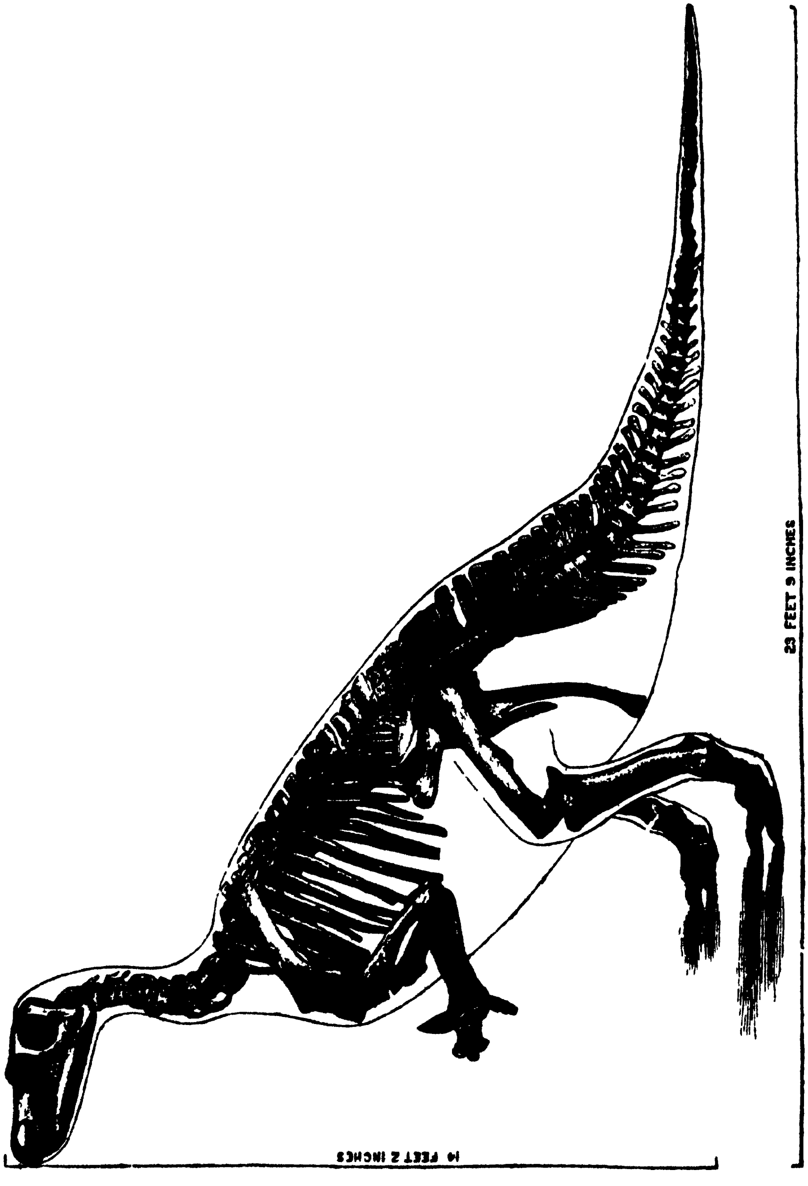

FIG. 421.—Cretaceous Deinosaur (Iguanodon). From the skeleton as restored and erected by MM. de Paw and Dollo in the Brussels Museum.

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[1] Leidy, *Smithson. Contrib.* 1865, No. 192; *Rep. U.S. Geol. and Geograph. Survey of Territories*, vol. i. (1873); Cope, *Rep. U.S. Geol. and Geograph. Survey of Territories*, vol. ii. (1875); *Amer. Naturalist*, 1878 *et seq.*; Marsh, *Amer. Journ. Science*, numerous papers in 3rd series, vols. i.-xlii. (1892).

According to an enumeration made a few years ago by Cope, but which is now below the truth, there were known 18 species of deinosaurs, 4 pterosaurs, 14 crocodilians, 13 sauropterygians or sea-saurians, 48 testudinates (turtles, &c.), and 50 pythonomorphs or sea-serpents. One of the most extraordinary of reptilian types was the *Discosaurus* or *Elasmosaurus*—a huge snake-like form 40 feet long, with slim arrow-shaped head on a swan-like neck rising 20 feet out of the water. This formidable sea-monster "probably often swam many feet below the surface, raising the head to the distant air for a breath, then withdrawing it and exploring the depths 40 feet below without altering the position of its body. It must have wandered far from land, and that many kinds of fishes formed its food is shown by the teeth and scales found in the position of its stomach" (Cope). The real rulers of the American Cretaceous waters were the pythonomorphic saurians or sea-serpents, in which group Cope includes forms like *Mosasaurus*, whereof more than 40 species have been discovered. Some of them attained a length of 75 feet or more. They possessed a remarkable elongation of form, particularly in the tail; their heads were large, flat, and conic, with eyes directed partly upwards. They swam by means of two pairs of paddles, like the flippers of the whale, and the eel-like strokes of their flattened tail. Like snakes, they had four rows of formidable teeth on the roof of the mouth, which served as weapons for seizing their prey. But the most remarkable feature in these creatures was the unique arrangement for permitting them to swallow their prey entire, in the manner of snakes. Each half of the lower jaw was articulated at a point nearly midway between the ear and the chin, so as greatly to widen the space between the jaws, and the throat must, consequently, have been loose and baggy like a pelican's. The deinosaurs were likewise well represented on the shores of the American waters. Among the known forms are *Hadrosaurus*, a kangaroo-like creature resembling the *Iguanodon*, and about 28 feet long; *Diclonius*, an allied form with a bird-like head and spatulate beak, probably frequenting the lakes and wading there for succulent vegetable food, interesting from its occurrence in the Laramie group of beds at the very close of the Cretaceous series; and *Lælaps*, which probably also walked erect, and resembled the *Megalosaurus*. Still more gigantic was the allied *Ornithotarsus*, which is supposed to have had a length of 35 feet. There were also in later Cretaceous time strange horned creatures such as *Ceratops* which, attaining a length of 25 or 30 feet, had a massive body, a pair of large and powerful horns, and a peculiar dermal armour. Akin to it were various deinosaurs united in the genus *Triceratops*, so named from the third rhinoceros-like nasal horn. Some of their skulls exceeded 6 feet in length, exclusive of the horny beak, and 4 feet in width, with horn-cores about 3 feet long. *Claosaurus* was another gigantic deinosaur not unlike the *Iguanodon*, with remarkably small fore-limbs compared with the massive hind legs.[1] Pterosaurs have likewise been obtained characterised by an absence of teeth (*Pteranodonts*), and some of which had a spread of wing of 20 to 25 feet.[1] Among the Chelonians one gigantic species is supposed to have measured upwards of 15 feet between the tips of the flippers.

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[1] Marsh, on Cretaceous Deinosaurs, *op. cit.* xxxvi. (1888) xxxviii. xxxix. xli. xlii. xliv. xlv. (1893).

The remains of birds have been met with both in Europe and in America among Cretaceous rocks. From the Cambridge Greensand bones of at least two species, referred to the genus *Enaliornis*, have been

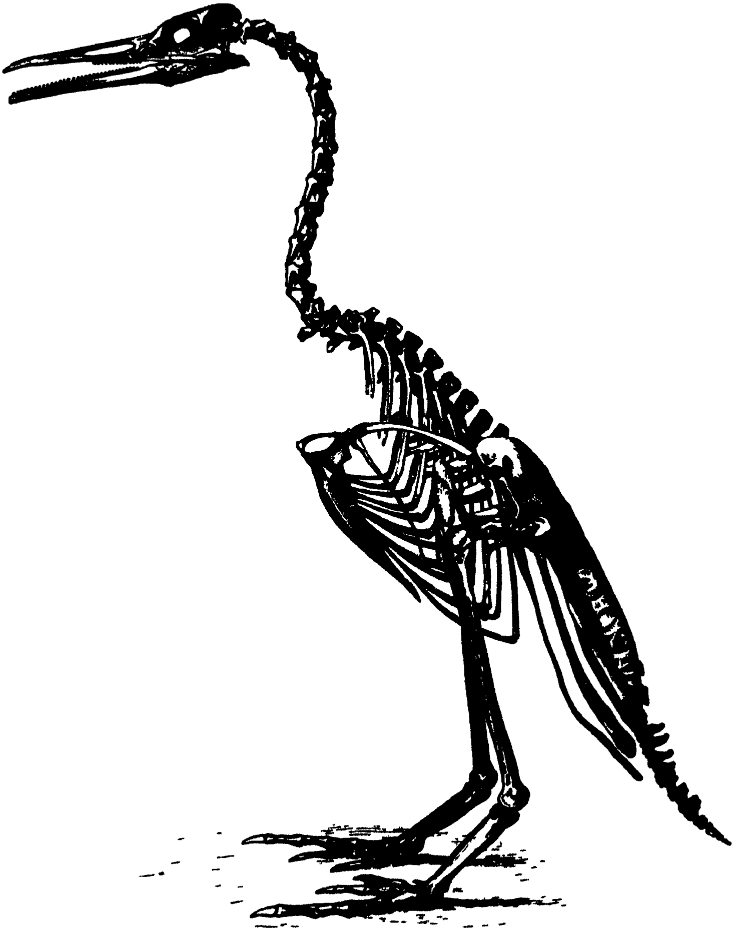

Fig. 422.—Cretaceous Bird.[2]
Hesperornis regalis, Marsh ($\frac{1}{10}$).

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[1] Marsh, on American Cretaceous Pterodactyles, *Amer. Journ. Sci.* i. (1871) iii. xi. xii. xxi. xxvii. (1884).

[2] For this restoration and Fig. 423 I am indebted to the kindness of my friend Professor Marsh.

obtained. These creatures are regarded by Professor Seeley as having osteological characters that place them with the existing natatorial birds.[1] From the American Cretaceous rocks nine genera and twenty species, represented at present by the remains of about 120 individuals, have been obtained. Among these by far the most remarkable are the *Odontornithes*, or toothed birds, from the Cretaceous beds of Kansas. Professor Marsh, who some years ago described these wonderfully preserved forms, has pointed out the interesting evidence they furnish of a reptilian ancestry.[2] In the most important and indeed unique genus, named by him *Hesperornis* (Fig. 422), the jaws were furnished with teeth implanted in a common alveolar groove, as in Ichthyosaurus; the wings were rudimentary or aborted, so that locomotion must have been entirely performed by the powerful hind limbs, with the aid of a broad, flat, beaver-like tail, which no doubt materially helped in steering the creature through the water. It must have been an admirable diver. Its long flexible neck and powerful toothed jaws would enable it to catch the most agile fish, while, as the lower jaws were united in front only by cartilage, as in serpents, and had on each side a joint that admitted of some motion, it had the power of swallowing almost any size of prey. *Hesperornis regalis*, the type species, must have measured about 6 feet from the point of the bill to the tip of the tail, and presented some resemblance to an ostrich. Of the other genera, *Ichthyornis* (Fig. 423) and *Apatornis* were distinguished by some types of structure pointing backward to a very lowly ancestry. They appear to have been small, tern-like birds, with powerful wings but small legs and feet. They possessed reptile-like skulls, with teeth set in sockets, but their vertebræ were bi-concave, like those of fishes. There were likewise forms which have been grouped in the genera *Graculævus*, *Laornis*, *Palæstringa*, and *Telmatornis*. Altogether the earliest known birds present characters of strong affinity with the Deinosaurs and Pterodactyles.[3]

Though mammalian remains had long been known to occur in the Triassic and Jurassic formations, none had been obtained from Cretaceous rocks, and this absence was all the more remarkable from the great abundance and perfect preservation of the reptilian forms in these rocks. But the blank has now been filled by the remarkable discovery in the Upper Cretaceous rocks of Dakota and Wyoming of a large series of jaws, teeth, and different parts of the skeletons of small mammals belonging to many individuals, and including not a few genera and species. They were found associated with remains of deinosaurs, crocodiles, turtles, ganoid fishes, and invertebrate fossils indicating brackish or fresh-water conditions. The mammalian forms show close affinities to the Triassic and Jurassic types. There are several distinct genera of small marsupials, others seem to be allied to the monotremes, but there are no carnivores, rodents, or ungulates. The genera proposed for them by

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[1] *Q. J. Geol. Soc.* 1876, p. 496.

[2] 'Odontornithes,' being vol. i. of *Memoirs of Peabody Museum of Yale College*, and also vol. vii. of *Geol. Explor. 40th Parallel*. "Birds with Teeth," *Rep. U.S. Geol. Surv.* 1881-82, p. 45.

[3] See Marsh, *U.S. Geol. Surv. Report*, 1881-82, p. 86.

Professor Marsh are *Cimolomys*, *Cimolodon*, *Nanomys*, *Dipriodon*, *Tripriodon*, *Selenacodon*, *Halodon*, *Camptomus*, *Dryolestes*, *Didelphops*, *Cimolestes*, *Pediomys*, *Stagodon*, *Platacodon*, *Oracodon*, and *Allacodon*.[1] More recently the discovery of a single small tooth in the Wealden series of Hastings is the first trace of mammalian life yet found in the Cretaceous formations of Europe. The specimen has been provisionally referred to the Purbeckian genus *Plagiaulax*.[2]

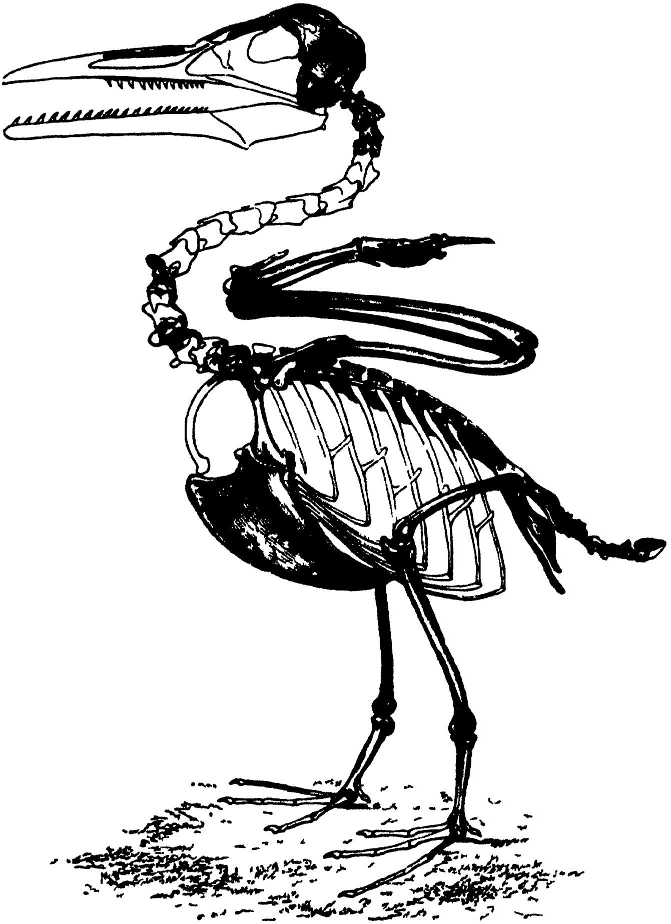

Fig 423.—Cretaceous Bird
Ichthyornis victor, Marsh (½)

§ 2. Local Development

The Cretaceous system, in many detached areas, covers a large extent of Europe From the south-west of England it spreads across the north of France, up to the base of the ancient central plateau of that country. Eastwards it ranges beneath the Tertiary and post-Tertiary deposits of the great plain, appearing on the north side at the southern end of Scandinavia and in Denmark, on the south side in Belgium and Hanover, round the flanks of the Harz, in Bohemia and Poland, eastwards into Russia, where it covers many thousand square miles, up to the southern end of the Ural chain. To the south of the central axis in France, it underlies the great basin of the Garonne, flanks the chain of the Pyrenees on both sides, spreads out largely over the eastern side of the Spanish tableland, and reappears on the west side of the crystalline axis of that region along the coast of Portugal. It is seen at intervals along the north and south fronts of the Alps, extending down the valley of the Rhone to the Mediterranean, ranging along the chain of the Apennines into Sicily and the north of Africa, and widening out from the eastern shores of the Adriatic through Greece, and along the northern base of the Balkans to the Black Sea, round the southern shores of which it passes in its progress into Asia, where it again covers an enormous area.

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[1] Marsh, *Amer. Journ. Sci.* xxxviii. (1889) pp. 81, 177, xliii. (1892) p. 249.

[2] A. Smith Woodward, *Nature*, xlv. (1891), p. 164.

A series of rocks covering so vast an extent of surface must needs present many differences of type, alike in their lithological characters and in their organic contents. They bring before us the records of a time when a continuous sea stretched over the centre and most of the south of Europe, covered the north of Africa, and swept eastwards to the far east of Asia. There were doubtless many islands and ridges in this wide expanse of water, whereby its areas of deposit and biological provinces may have been more or less defined. Some of these barriers can still be traced, as will be immediately pointed out.

While there is sufficient palæontological similarity to allow a general parallelism to be drawn among the Cretaceous rocks of western Europe, there are yet strongly marked differences pointing to very distinct conditions of life, and probably, in many cases, to disconnected areas of deposit. Having regard to these geographical variations, a distinct northern and southern province, as above stated (p. 920), can be recognised; but Gumbel has proposed a further grouping into three great regions: (1) the northern province, or area of White Chalk with *Belemnitella*, comprising England, northern France, Belgium, Denmark, Westphalia, &c.; (2) the Hercynian province, or area of *Exogyra columba*, embracing Bohemia, Moravia, Saxony, Silesia, and Central Bavaria; and (3) the southern province, or area of Hippurites, including the regions of France south of the basin of the Seine, the Alps, and southern Europe.[1]

Britain.[2]—The Purbeck beds bring before us evidence of a great change in the geography of England towards the close of the Jurassic period. They show how the floor of the sea, in which the thick and varied formations of that period were deposited, came to be gradually elevated, and how into pools of fresh and brackish water the leaves, insects, and small marsupials of the adjacent land were washed down. These evidences of terrestrial conditions are followed in the same region by a vast delta-formation, that of the Weald, which accumulated over the south of England, while marine strata were being deposited in the north. Hence two types of Lower Cretaceous sedimentation occur, one where the strata are fluviatile (Wealden), the other where they are marine (Neocomian). The Upper Cretaceous groups, extending continuously from the coasts of Dorsetshire to those of Yorkshire, show that the diversities of sedimentation in Lower Cretaceous time were effaced by a general submergence of the whole area beneath the sea in which the Chalk was deposited. Arranged in descending order, the following are the subdivisions of the English Cretaceous rocks:—

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[1] 'Geognost. Beschreib. Ostbayer. Grenzgebirg.'

[2] Consult Conybeare and Phillips, 'Geology of England and Wales,' 1822; Fitton, *Ann. Philos.* 2nd ser. viii. 379; *Trans. Geol. Soc.* 2nd ser. iv. 103; Dixon's 'Geology of Sussex,' edit. T. Rupert Jones, 1878; Phillips's 'Geology of Oxford and the Thames Valley'; H. B. Woodward's 'Geology of England and Wales,' 2nd edit. Special papers on the English Cretaceous formations are quoted in subsequent footnotes.

<table>
<tr><th colspan="3">English Stratigraphical Subdivisions.</th><th></th><th colspan="3">Palæontological Zones.</th></tr>
<tr><td colspan="3">UPPER CRETACEOUS.</td><td></td><td colspan="3">Danian, wanting.</td></tr>
<tr><td rowspan="3">Upper Chalk with Flints.</td><td colspan="2">Chalk of Norwich, Studland Bay</td><td rowspan="3">Senonian.</td><td>Campanian.</td><td>Zone of Belemnitella mucronata.</td><td>Horizon of B. mucronata alone.
„ B. mucronata and B. quadrata.
„
„</td></tr>
<tr><td colspan="2">Chalk of Brighton, Margate, Bridlington, Salisbury</td><td rowspan="2">Santonian.</td><td>Zone of Marsupites ornatus.</td><td>„ numerous sponges.
„ Inoceramus lingua and few sponges.</td></tr>
<tr><td colspan="2">Chalk of Broadstairs, Flamborough Head
Chalk of Dover</td><td colspan="2">Zone of Micraster cor-anguinum, var.
„ M. cor-testudinarium.</td></tr>
<tr><td rowspan="3">Middle Chalk (without Flints).</td><td colspan="2">Hard nodular Chalk of Dover, &c., "Chalk Rock"</td><td rowspan="3">Turonian.</td><td rowspan="2">Angoumian.</td><td colspan="2">Zone of Holaster planus.</td></tr>
<tr><td colspan="2">Chalk without flints, Dover, &c.</td><td colspan="2">„ Terebratulina gracilis.</td></tr>
<tr><td colspan="2">Nodular Chalk of Shakespeare's Cliff, &c., "Melbourne Rock"</td><td>Ligerian.</td><td colspan="2">Zone of Inoceramus labiatus (mytiloides), and Rhynchonella Cuvieri.</td></tr>
<tr><td rowspan="2">Lower Chalk.</td><td colspan="2">Grey Chalk of Folkestone, &c.; Totternhoe Stone.
Chalk Marl.
Red Chalk of Norfolk.
"Chloritic Marl," Glauconitic Marl.</td><td rowspan="4">Cenomanian.</td><td>Carentonian.</td><td>Zone of Belemnitella plena (Belemnites plenus).
Zone of Holaster subglobosus.</td><td>Horizon of Ammonites rothomagensis.
„ A. varians.
„ Plocoscyphia mæandrina.</td></tr>
<tr><td colspan="2">Cambridge Greensand</td><td rowspan="3">Rothomagian.</td><td colspan="2">Zone of "Craie glauconieuse" of France.</td></tr>
<tr><td rowspan="2">Upper Greensand.</td><td colspan="2">Warminster beds, &c.</td><td colspan="2">„ Pecten asper.</td></tr>
<tr><td colspan="2">Blackdown beds, &c.</td><td colspan="2">„ Ammonites (Schlonbachia) inflatus.</td></tr>
<tr><td rowspan="2">Gault.</td><td colspan="2">Upper</td><td rowspan="2">Gault.</td><td rowspan="2">Albian.</td><td colspan="2">Ammonites cristatus, A. auritus, A. lautus.</td></tr>
<tr><td colspan="2">Lower</td><td colspan="2">Hamites rotundus.</td></tr>
<tr><td colspan="3">LOWER CRETACEOUS.</td><td rowspan="5">Neocomian (including Urgonian, Aptian, and part of the Albian of French authors).</td><td colspan="3" rowspan="2"></td></tr>
<tr><td></td><td>Southern Type.
(Fluviatile, and in upper part marine.)</td><td>Northern Type.[1]
(Marine.)</td></tr>
<tr><td>Lower Greensand.</td><td>Sands, clays, limestones, &c., in Kent, Surrey, Sussex, Hampshire.</td><td rowspan="3">Below the Red Chalk, at Speeton, on the Yorkshire coast, clays and marls, in apparently continuous sequence, pass down into Neocomian clays and shales (Speeton clay), which are less than 300 feet thick, and shade down into Kimeridge Clay. They are grouped in four zones. Their upper portions are equivalent to the Carstone and Tealby limestone and clay of Lincolnshire, and their lower parts to the Claxby Ironstone and Spilsby Sandstone.</td><td colspan="3">4. Zone of Belemnites minimus, perhaps including equivalents of Lower Gault.
3. Zone of Belemnites semicanaliculatus (?) (B. brunsvicensis), with Ammonites Deshayesi, species of Crioceras, Ancyloceras, Hamites, Rostellaria Phillipsii, Exogyra sinuata, Panopæa neocomiensis, &c.</td></tr>
<tr><td rowspan="2">Wealden.</td><td>Weald Clay.</td><td colspan="3">2. Zone of Belemnites jaculum, with Ammonites noricus, A. speetonensis, A. astierianus, Crioceras Duvalii, C. puzosianum, Rostellaria Phillipsii, Exogyra sinuata, Pecten cinctus, Nucula subangulata, &c.</td></tr>
<tr><td>Hastings sands and clays, passing down into Purbeck beds.</td><td colspan="3">1. Zone of Belemnites lateralis, with Amm. gravesianus, A. noricus, A. rotula, Crioceras, Exogyra sinuata, Panopæa plicata, Pecten lens, P. cinctus, Serpula vertebralis.</td></tr>
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[1] See G. W. Lamplugh, *Quart. Journ. Geol. Soc.* xlv. (1889) p. 575; *Brit. Assoc.* (1890) p. 808; 'Argiles de Speeton et leurs équivalents,' by A. Pavlow and G. W. Lamplugh in *Bull. Soc. Imp. Nat. Moscou*, 1891.

LOWER CRETACEOUS (NEOCOMIAN[1]).—Between the top of the Jurassic system and the strata known as the Gault, there occurs an important series of deposits to which, from their great development in the neighbourhood of Neuchâtel in Switzerland, the name of Neocomian has been given. This series, as already remarked, is represented in England by two distinct types of strata. In the southern counties, from the Isle of Purbeck to the coast of Kent, there occurs a thick series of fresh-water sands and clays termed the Wealden series. These strata pass up into a minor marine group known as the Lower Greensand, in which some of the characteristic fossils of the Upper Neocomian rocks occur. The Wealden beds of England therefore form a fluviatile equivalent of the continental Neocomian formations, while the Lower Greensand represents the later marginal deposits of the Neocomian sea, which gradually usurped the place of the Wealden estuary. The second type, seen in the tract of country extending from Lincolnshire into Yorkshire, contains the deposits of deeper water, forming the westward extension of an important series of marine formations which stretch for a long way into central Europe.

Neocomian.[2]—The marine Neocomian strata of England are well exposed on the cliffs of the Yorkshire coast at Filey, where they occur in an argillaceous deposit long known as the "Speeton Clay." This deposit is now shown to contain an interesting continuous section of marine strata from the Kimeridge Clay to the top of the Lower Cretaceous, or even into the Upper Cretaceous series. It has been carefully studied by Mr. Lamplugh and by Professors Pavlow and Nikitin, by whom it has been brought into comparison with the Neocomian rocks of Russia. The lower part of the "Speeton Clay" consists of hard dark bituminous shales with large septarian nodules and many crushed fossils. Among these remains there occur *Belemnites Oweni*, *Ammonites* sp., *Lingula ovalis*, *Discina latissima*, *Ostrea gibbosa*, *Lucina minuscula*, &c. These strata are referred to the higher part of the Kimeridge Clay. They are succeeded conformably by the "zone of *Belemnites lateralis*," consisting of dark, pale, and banded clays with the fossils mentioned in the foregoing table. At the base of the zone lies a "coprolite bed," and its top is taken at a "compound nodular bed" rich in fossils (*Bel. lateralis*, *Amm. noricus*, *A. rotula*, *Avicula inæquivalvis*, *Pecten cinctus*, &c.) The total thickness of this zone is about 34 feet. It is overlain by the "zone of *Belemnites jaculum*," consisting likewise of various dark and striped clays and bands of nodules, the whole having a thickness of about 125 feet. While the underlying zone has obvious Jurassic affinities, this zone is unmistakably Lower Cretaceous. The characteristic belemnite ranges through 120 feet of the section with hardly any trace of another species. *Ammonites noricus* occurs in the lower 30 feet of the zone, and is succeeded by *A. speetonensis*. An interesting palæontological feature in this zone is the occurrence of abundant tests of *Echinospatangus cordiformis*, a highly characteristic Neocomian type. The "zone of *Belemnites semicanaliculatus* (?)" is seldom seen in complete section, owing to the slipping of the cliffs and the detritus on the foreshore. It consists of dark clays 100 feet thick or more. Above it a few feet of mottled green and yellow clays form the top of the Speeton Clay. These strata compose the zone of *Belemnites minimus*, and contain also *B. attenuatus*, *B. ultimus*, *Inoceramus concentricus*, *I. sulcatus*, &c. Some of their fossils are found in the Gault, and it has been suggested that they may represent here the Lower Gault, while the Red Chalk above may be the equivalent of the Upper Gault.[3]

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[1] Neocomian, from Neocomum, the old name of Neuchâtel in Switzerland.

[2] Fitton, *Trans. Geo. Soc.* 2nd. ser. iv. (1837) 103 ; *Proc. Geol. Soc.* iv. pp. 198, 208 ; *Q. J. Geol. Soc.* i. Consult on marine Neocomian type Young and Bird, 'Survey of the Yorkshire Coast' (1828), 2nd edit. pp. 58-64 ; J. Phillips, 'Geology of Yorkshire,' p. 124. J. Leckenby, *Geologist*, ii. (1859) p. 9. Judd, *Q. J. Geol. Soc.* xxiv. (1868) 218 ; xxvi. 326 ; xxvii. 207 ; *Geol. Mag.* vii. 220 ; C. J. A. Meyer, *Q. J. Geol. Soc.* xxviii. 243 ; xxix. 70. A. Strahan, *op. cit.* xlii. (1886) p. 486 ; *Mem. Geol. Surv.* sheet 84.

[3] G. W. Lamplugh, *op. cit.*

In Lincolnshire the marine Neocomian series is likewise developed. Rising to the surface from beneath the Chalk, the highest and lowest strata are chiefly sand and sandstone; the middle portion (Tealby series) clays and oolitic ironstones. According to Mr. Lamplugh, the Spilsby Sandstone and the Claxby Ironstone of this county, forming the base of the Neocomian series and resting on Upper Kimeridge shales, are equivalents of the zone of *Belemnites lateralis* at Speeton. The Tealby Clay, which overlies them, is regarded as representing the zone of *B. jaculum*, the Tealby Limestone the zone of *B. semicanaliculatus* (?), while the Carstone at the top immediately below the Red Chalk is placed on the horizon of the marls with *B. minimus*.[1] The Carstone ranges into Norfolk, and perhaps represents the entire "Lower Greensand" of central and southern England.

Wealden.—In the southern counties a very distinct assemblage of strata is met with.[2] It consists of a thick series of fluviatile deposits termed Wealden (from the Weald of Sussex and Kent, where it is best developed), surmounted by a group of marine strata ("Lower Greensand"), in which Upper Neocomian fossils occur. It would appear that the fresh-water conditions of deposit, which began in the south of England towards the close of the Jurassic period, when the Purbeck beds were laid down, continued during the whole of the long interval marked by the Lower and Middle Neocomian formations, and only in Upper Neocomian times finally merged into ordinary marine sedimentation. The Wealden series has a thickness of over 2000 feet, and in Sussex and Kent consists of the following subdivisions in descending order:—

Weald Clay	1000 feet.
Hastings Sand group composed of—	
3. Tunbridge Wells Sand (with Grinstead Clay) . . .	140 to 380 ,,
2. Wadhurst Clay	120 ,, 180 ,,
1. Ashdown Sand (with Fairlight Clays in lower part) .	400 or 500 ,,

In the Isle of Wight these subdivisions cannot be made out, and the total visible thickness of strata (sandstones, sands, clays, and shales) is only about half of what can be observed on the mainland farther east, but the base of the series cannot be seen. Westward at Punfield, on the coast of Dorsetshire, the Wealden strata are exposed on the shore, and are there estimated to be from 1500 to 2000 feet thick. On the whole the Wealden series is thickest towards the west.

The sandy and clayey sediments composing the Wealden series precisely resemble the deposits of a modern delta. That such was really their origin is borne out by their organic remains, which include terrestrial plants (*Equisetum*, *Sphenopteris*, *Alethopteris*, *Thuyites*, cycads, and conifers), fresh-water shells (*Unio*, 10 species; *Cyrena*, 5 species; *Paludina*, *Vicarya*, *Melania*, &c.), with a few estuarine or marine forms, as *Ostrea*, *Exogyra*, and *Mytilus*, and ganoid fishes (*Lepidotus*) like the gar of American rivers. Among the spoils of the land floated down by the Wealden river were the carcases of huge deinosaurian reptiles (*Cetiosaurus*, *Titanosaurus*, *Iguanodon*, *Hylæosaurus*, *Polacanthus*, *Megalosaurus*, *Vectisaurus*, *Hypsilophodon*), long-necked plesiosaurs, and winged pterodactyles. The deltoid formation, in which these remains occur, extends in an east and west direction for at least 200, and from north to south for perhaps 100 miles. Hence the delta may have been nearly 20,000 square miles in area. It has been compared with that of the Quorra; in reality, however, its extent must have been greater than its present visible area, for it has suffered from denudation, and is to a large extent concealed under more recent formations. The river probably descended from the north-west, draining a wide area, of which the existing mountain groups of Britain are perhaps merely fragments.

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[1] See A. J. Jukes-Browne, 'Geology of East Lincolnshire' in *Mem. Geol. Surv.* sheet 84 (1887); G. W. Lamplugh, 'Argiles de Speeton,' *Bull. Soc. Imp. Nat. Moscou* (1891).

[2] On the Wealden or fluviatile type consult, besides the works quoted on p. 937, Mantell's 'Fossils of the South Downs,' 4to, 1822; Topley, 'Geology of the Weald,' in *Mem. Geol. Surv.* 8vo, 1875. Bristow and Strahan, 'Geology of the Isle of Wight,' 2nd edit. (1889), in *Mem. Geol. Surv.* (list of Wealden fossils, p. 258).

Lower Greensand.—The Wealden series is succeeded conformably by the group of arenaceous strata which has long been known under the awkward name of "Lower Greensand." This group consists mainly of yellow, grey, white, and green sands, but includes also beds of clay and bands of limestone and ironstone. It has been subdivided in descending order as under:—

Folkestone beds (Lower Albian in the upper part)	70 to 100 feet.
Sandgate beds (Aptian)	75 „ 100 „
Hythe beds (Aptian)	80 „ 300 „
Atherfield Clay (Urgonian), resting on Wealden	20 „ 60 „

These strata appear to represent the continental series up into the base of the Albian stage. The Atherfield Clay is well developed at Atherfield, on the south coast of the Isle of Wight. It contains an abundant series of fossils, among which are *Toxaster complanatus*, *Terebratula sella*, *Exogyra* (*Ostrea*) *Couloni*, *Ostrea Leymeriei*, *Perna Mulleti*, *Arca Raulini*, and others which indicate an Urgonian horizon for this band.[1] In the Hythe beds are found *Plicatula placunea*, *Ammonites Deshayesi*, *A. cornuelianus*, *Ancyloceras gigas*, *A. Hilsii*, *Belemnites semicanaliculatus*, *Crioceras Bowerbankii*. Some of these fossils are found also in the Sandgate beds, while the upper part of the Folkestone beds yields likewise *Amm. mamillaris*. The Hythe and Sandgate beds may therefore represent the Aptian stage, while the Folkestone subdivision may be regarded as the equivalent of the lower part of the Albian.[2]

Of the total assemblage of fossils from the "Lower Greensand," about 300 in number, only 18 or 20 per cent pass up into the Upper Cretaceous series. This marked palæontological break, taken in connection with a great lithological change, and with an unconformability which in Dorset brings the Gault directly upon the Kimeridge Clay, shows that a definite boundary line can be drawn between the lower and upper parts of the Cretaceous system in England.

UPPER CRETACEOUS.—Three leading lithological groups have long been recognised as constituting the Upper Cretaceous series of England. First, a band of clay termed the Gault; second, a variable and inconstant group of sand and sandstones called the "Upper Greensand"; and, third, a massive calcareous formation chiefly composed of white chalk. But the foreign nomenclature, founded mainly on palæontological considerations, and given in the foregoing table (p. 938), may now be adopted, as it brings the English Upper Cretaceous groups into recognisable parallelism with their continental equivalents.

Gault[3] **(Albian).**—A dark, stiff, blue, sometimes sandy or calcareous clay, with layers of pyritous and phosphatic nodules and occasional seams of green sand. It varies from 100 to more than 300 feet in thickness, forming a marked line of boundary between the Upper and Lower Cretaceous rocks, overlapping the latter and resting sometimes even on the Kimeridge Clay. One of the best sections is that of Copt Point, on the coast near Folkestone, where the following subdivisions have been established by Messrs. De Rance and Price:[4]—

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[1] For a list of the fossils of the Atherfield Clay and other members of the Lower Greensand in the Isle of Wight, see the *Geol. Surv. Mem.* on that island cited on the foregoing page.

[2] For explanations of these and the other Cretaceous stratigraphical terms, which have been chiefly founded on the names of continental localities or districts where the several subdivisions are especially well developed, see the footnotes on the succeeding pages.

[3] "Gault" is a Cambridgeshire provincial name.

[4] C. E. De Rance, *Geol. Mag.* v. p. 163; i. (2) p. 246; F. G. H. Price, *Q. J. Geol. Soc.* xxx. p. 342; 'The Gault,' 8vo, London, 1879.

Upper Greensand.

Upper Gault.

11. Pale grey marly clay (56 ft. 3 in.), characterised by *Ammonites* (*Schlönbachia*) *rostratus* (*inflatus*), *A. Goodhalli*, *Ostrea frons*, *Inoceramus Crispii*.
10. Hard pale marly clay (5 ft. 1 in.), with *Kingena lima*, *Rostellaria maxima*, *Plicatula pectinoides*, *Pecten raulinianus*, *Pentacrinus Fittoni*, *Cidaris gaultina*.
9. Pale grey marly clay (9 ft. 4½ in.), with *Inoceramus sulcatus*, *Ammonites varicosus*, *Pholadomya fabrina*, *Pleurotomaria Gibbsii*, *Scaphites æqualis*.
8. Darker clay, with two lines of nodules and rolled fossils (9½ in.), with *Ammonites cristatus*, *A. Beudanti*, *Pholas sanctæ-crucis*, *Mytilus Galliennei*, *Cucullæa glabra*, *Cyprina quadrata*.

Lower Gault.

7. Dark clay (6 ft. 2 in.) highly fossiliferous, with *Ammonites auritus*, *Nucula bivirguta*, *N. ornatissima*, *Aporrhais Parkinsoni*, *Fusus indecisus*, *Pteroceras bicarinatum*.
6. Dark mottled clay (1 ft.), *Ammonites denarius*, *A. cornutus*, *Turrilites hugardianus*, *Necrocarcinus Bechei*.
5. Dark spotted clay (1 ft. 6 in.), *Ammonites* (*Hoplites*) *lautus*, *Astarte dupiniana*, *Solarium moniliferum*, *Phasianella ervyana*, numerous corals.
4. Paler clay (4 in.) *Ammonites Delaruei*, *Natica obliqua*, *Dentalium decussatum*, *Fusus gaultinus*.
3. Light fawn-coloured clay, "crab-bed" (4 ft. 6 in.) with numerous carapaces of crustaceans (*Palæocorystes Stokesii*, *P. Broderipii*), *Pinna tetragona*, *Hamites attenuatus*.
2. Dark clay marked by the rich colour of its fossils (4 ft. 3 in.), *Ammonites auritus*, *Turrilites elegans*, *Ancyloceras spinigerum*, *Aporrhais calcarata*, *Fusus itierianus*, *Cerithium trimonile*, *Corbula gaultina*, *Pollicipes rigidus*.
1. Dark clay, dark greensand, and pyritous nodules (10 ft. 1 in.), *Ammonites interruptus*, *Crioceras astierianum*, *Hamites rotundus*.

Lower Greensand.

Mr. Price remarks that, out of 240 species of fossils collected by him from the Gault only 39 are common to the lower and upper divisions, while 124 never pass up from the lower and 59 appear only in the upper. The lower Gault seems to have been deposited in a sea specially favourable to the spread of gasteropods, of which 46 species occur in that division of the formation. Of these only six appear to have survived into the period of the upper Gault, where they are associated with five new forms. Of the lamellibranch fauna, numbering in all 73 species, 39 are confined to the lower division, four are peculiar to the passage-bed (No. 8), 14 pass up into the upper division, where they are accompanied by 16 new forms. About 46 per cent of the Gault fauna pass up into the upper Greensand.[1]

Cenomanian.[2]—Under the name of *Upper Greensand* have been comprised sandy strata, often greenish in colour, which are now known to belong to different horizons of the Cretaceous series. If the term is to be retained at all, its use must be accompanied with some palæontological indication of the true position of the beds to which it is applied. According to the researches of Dr. C. Barrois, the English Upper Greensand, as originally defined by Berger, Inglefield, Webster, Fitton, and others, has no such distinct assemblage of fossils as might have been supposed from its lithological characters, but appears to be everywhere divisible into two groups: a lower containing *Ammonites rostratus* (*inflatus*), and an upper marked by *Pecten asper*. These strata are well developed in Devonshire and Somerset. There the "Blackdown beds" below, linked with the Gault (of which Godwin-Austen regarded them as a sandy littoral representative) contain a numerous fauna, including *Ammonites Goodhalli*, *Hamites alternatus*, *Cytherea parva*, *Venus submersa*, *Arca glabra*, *Trigonia alæformis*, *Pecten laminosus*, *Janira quinquecostata*, *J. quadricostata*, *J. æquicostata*, *Exogyra conica*, *Vermicularia polygonalis;* while the "Warminster beds" above correspond to the "zone of *Holaster nodulosus*" of M. Hébert, and the "zone of *Pecten asper*" of Dr. Barrois, and contain *Ammonites* (*Schlonbachia*) *varians*, *A. Mantelli*, *A. Coupei*, *Belemnites ultimus*, *Pecten asper*, *Ostrea frons* (*carinata*), *Terebratella pectita*, *Terebratula biplicata*, *T. squamosa*, *Rhynchonella compressa*, *R. latissima*, *Pseudodiadema Michelini*, *Peltastes clathratus*, *Discoidea subucula*, &c. A tolerably abundant series of corals has been obtained from the Devonshire Upper Greensand, no fewer than 21 species having been described.[1]

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[1] The foraminifera of the Gault at Folkestone, with reference to the zones here given, have been described by F. Chapman, *Journ. R. Micros. Soc.* 1891, p. 565 ; 1892, pp. 321, 749.

[2] From Cœnomanum, the old Latin name of the town Mans in the department of Sarthe. The old lithological subdivisions of the English Upper Cretaceous groups have been found to be wanting in palæontological precision, and are gradually being supplanted by the terms proposed by D'Orbigny, which have long been in use in France. These terms are here employed, but their equivalents in the old nomenclature will be understood from the table on p. 938. To M. Hébert geology is mainly indebted for the thorough detailed study and classification to which the Upper Cretaceous formations of the Anglo-Parisian basin have been subjected. In 1874 he published a short memoir, in which the Chalk in Kent was subdivided into zones equivalent to those in the Paris basin (*Bull. Soc. Géol. France*, 1874, p. 416). Subsequently the same task was taken up and extended over the rest of the English Cretaceous districts, by Dr. Charles Barrois ('Recherches sur le Terrain Crétacé supérieur de l'Angleterre et de l'Irlande,' Lille, 1876). The first English geologist who appears to have attempted the palæontological subdivision of the Chalk was Mr. Caleb

The so-called Greensand of Cambridge (pp. 931, 938), a thin glauconitic marl, with phosphatic nodules and numerous (possibly ice-borne) erratic blocks, was formerly classed with the Upper Greensand, but has recently been shown to be the equivalent of the Glauconitic Marl, forming really the base of the Chalk Marl and lying unconformably upon the Gault, from the denudation of which its rolled fossils have been derived.[2]

Lower Chalk.—The thick calcareous deposit known as the Chalk is classed now in three chief divisions—Lower, Middle, and Upper. Under the name of Lower Chalk are included the groups of the Glauconitic or Chloritic Marl, the Chalk Marl, and the Grey Chalk up to the top of the zone of *Belemnitella plena* and base of the "Melbourne Rock."

Glauconitic (*Chloritic*) *Marl.*—This name has been applied to a local white, or light yellow, chalky marl lying below the true Chalk, and marked by the occurrence of grains of glauconite (not chlorite) and phosphatic nodules. It varies up to 15 feet in thickness. Among its fossils are *Ammonites laticlavius*, *A. Coupei*, *A. Mantelli*, *A. varians*, *Nautilus lævigatus*, *Turrilites tuberculatus*, *Solarium ornatum*, *Plicatula inflata*, *Terebratula biplicata*. It forms the base of the *Holaster subglobosus* zone.

Chalk Marl is the name given to an argillaceous chalk forming with the chloritic marl, where the latter is present, the base of the true Chalk formation. This subdivision is well exposed on the Folkestone cliffs, also westward in the Isle of Wight, where a thickness of upwards of 100 feet has been assigned to it. Among its characteristic fossils are *Plocoscyphia mæandrina*, *Holaster lævis* (var. *nodulosus*), *Rhynchonella Martini*, *Inoceramus striatus*, *Lima globosa*, *Plicatula inflata*, *Ammonites cenomanensis*,

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Evans ('Sections of Chalk,' Lewes, 8vo, 1870; *for the Geologists' Association*). See also W. Whitaker, "Geology of the London Basin" and "Geology of London," in *Geol. Survey Memoirs*, and authors there cited. A tolerably full bibliography will be found in Dr. Barrois' volume.

[1] On the literature of the Blackdown beds, see W. Downes, *Q. J. Geol. Soc.* xxxviii. (1882) p. 75, where a list of their fossils is given. The corals are described by P. Martin Duncan, *Q. J. Geol. Soc.* xxxv. p. 90.

[2] Jukes-Browne, *Q. J. Geol. Soc.* xxxi. p. 272, xxxiii. p. 485; "Geology of Cambridge," *Mem. Geol. Surv.* 1881; *Geol. Mag.* 1877.

A. falcatus, A. Mantelli, A. navicularis, A. varians, Scaphites æqualis, Turrilites costatus.

At Hunstanton in Norfolk, likewise in Lincolnshire and Yorkshire, as already (p. 939) referred to, the "Red Chalk"—a ferruginous, hard, nodular chalk zone (4 feet), lies at the base of the Chalk and rests on the Upper Neocomian "Carstone," the true Gault being there absent, although it occurs a few miles farther south.[1] Its proper horizon has been the subject of much discussion; but it probably belongs to the Chalk Marl. Bands of red and yellow chalk occur in the lower parts of the Chalk above the horizon of the "Red Chalk" in Lincolnshire and Suffolk.[2]

Grey Chalk.—The lower part of the Chalk has generally a somewhat greyish tint, often mottled and striped. In Bedfordshire and adjoining counties a band of hard grey sandy chalk, from 6 to 15 feet thick, containing 8 per cent of silica and in places much glauconite, is known as the Totternhoe Stone,[3] and forms the base of the Grey Chalk, which as a stage comprises the palæontological zones of *Holaster subglobosus* and *Belemnitella plena.* It attains its fullest development along the shore-cliffs of Kent, where it has a thickness of about 200 feet. According to Mr. F. G. H. Price,[4] it is there divisible into five beds or sub-stages. Of these the lowest, 8 feet thick (= lower part of the *Ammonites varians* zone), contains among other fossils *Discoidea subucula, Pecten Beaveri, Ammonites varians;* the second bed (11 feet) contains many fossils, including *Ammonites rothomagensis, A. Mantelli, A. lewesiensis* (= part of *A. varians* zone); the third bed (2 feet 9 inches), also abundantly fossiliferous, contains among other forms *Peltastes clathratus, Hemiaster Morrisii, Terebratula rigida, Rhynchonella mantelliana, Ammonites rothomagensis, A. varians;* this and the two underlying beds are regarded as comprising the zone of *Ammonites rothomagensis* and *A. varians;* the fourth sub-stage, or zone of *Holaster subglobosus* (148 feet), contains among its most characteristic fossils *Discoidea cylindrica, Holaster subglobosus, Goniaster mosaicus,* and in its upper part *Belemnitella plena;* the fifth bed, or zone of *Belemnitella plena,* consisting of yellowish-white gritty chalk (4 feet), forms a well-defined band between the Grey Chalk and the overlying lower subdivision of the White Chalk (Turonian); it contains few fossils, among which are *Belemnitella plena, Hippurites* (*Radiolites*) *Mortoni, Ptychodus.*

In Cambridgeshire the Chalk Marl is covered by a band of harder stone (Totternhoe Stone), passing up into sandy and then nearly pure white chalk, and these strata, equivalents of the Chalk Marl and Grey Chalk, are probably separated by a palæontological and stratigraphical break from the next overlying (Turonian) member of the series.[5] According to the original classification of M. Hebert, this zone of *Belemnitella plena* is placed at the base of the Turonian group; by Dr. Barrois it is made the summit of the Cenomanian. The latter view receives support from traces of a break and denudation above this zone in England.

Middle Chalk, Turonian.[6]—This division comprises the "Lower White Chalk without flints," and is marked off at the base by a band of hard yellow and white nodular chalk, locally known in Cambridgeshire as "rag," and termed by geologists the Melbourne Rock. It is about 8 or 10 feet thick, and forms a convenient band in mapping out the subdivisions of the Chalk. It contains *Rhynchonella Cuvieri*, *Terebratulina striata*, *Inoceramus Cuvieri*, *Spondylus striatus*, *Ammonites peramplus*, &c.[1]

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[1] See Whitaker, *Geol. Mag.* 1883, p. 22; *Proc. Geol. Assoc.* viii. No. 3 (1883), p. 133. This author gives a full description and bibliography of the Red Chalk in *Proc. Norwich Geol. Soc.* i. part vii. (1883) p. 212.

[2] A. J. Jukes-Browne, *Geol. Mag.* 1887, p. 24.

[3] For the list of fossils of this bed in Norfolk and Suffolk see Jukes-Browne and W. Hill, *Quart. Journ. Geol. Soc.* 1887, p. 575.

[4] *Q. J. Geol. Soc.* xxiii. p. 436.

[5] A. J. Jukes-Browne, *Geol. Mag.* 1880, p. 250. See also the same author in "Geology of the Neighbourhood of Cambridge" (*Mem. Geol. Surv.*), and *Quart. Journ. Geol. Soc.* 1886, p. 216; 1887, p. 544.

[6] From Touraine, where the marly chalk is well developed.

The White Chalk of England and north-west France forms one of the most conspicuous members of the great Mesozoic suite of deposits. It can be traced from Flamborough Head in Yorkshire across the south-eastern counties to the coast of Dorset. Throughout this long course, its western edge usually rises somewhat abruptly from the plains as a long winding escarpment, which from a distance often reminds one of an old coast-line. The upper half of the deposit is generally distinguished by the presence of many nodular layers of flint. With the exception of these enclosures, however, the whole formation is a remarkably pure white pulverulent dull limestone, meagre to the touch, and soiling the fingers. Composed mainly of crumbled foraminifera, urchins, mollusks, &c., it must have been accumulated in a sea tolerably free from sediment, like some of the foraminiferal ooze of the existing sea-bed. There is, however, no evidence that the depth of the water at all approached that of the abysses in which the present Atlantic globigerina-ooze is being laid down. Indeed, the character of the foraminifera, and the variety and association of the other organic remains, are not like those which have been found to exist now on the deep floor of the Atlantic, but present rather the characters of a shallow-water fauna.[2] Moreover, the researches of M. Hébert have shown that the Chalk is not simply one continuous and homogeneous deposit, but contains evidence of considerable oscillations, and even perhaps of occasional emersion and denudation of the sea-floor on which it was laid down. The same observer believed that enormous gaps occur in the Upper Cretaceous series of the Anglo-Parisian basin, some of which are to be supplied from the centre and south of France (*postea*, p. 951).

Following the modern classification, we find that the old subdivision of "Chalk without flints" agrees on the whole with the Turonian section of the system. This division, as above remarked, appears in some places to lie unconformably upon the members below it, from which it is further separated by a marked zoological break. Nearly all the Cenomanian species now disappear, save two or three cosmopolitan forms. The echinoderms and brachiopods are entirely replaced by new species.[3] Not only is the base of the Turonian group defined by a stratigraphical hiatus, but its summit is marked by the "Nodular Chalk" of Dover and the hard Chalk-rock, which appear to indicate another stratigraphical break in what was formerly believed to be an uninterrupted deposit of chalk. The three Turonian palæontological zones, so well established in France, are also traceable in England. As exposed in the splendid Kent cliffs, the base of the English beds is formed by a well-marked band (32 feet) of hard gritty chalk, made up of fragments of *Inocerami* and other organisms.[4] Fossils are here scarce; they include *Inoceramus labiatus* (which begins here), *Rhynchonella Cuvieri*, *Echinoconus subrotundus*, *Cardiaster pygmæus*. Above this basement bed lies the massive Chalk without flints, full of fragments of *Inoceramus labiatus*, with *I. Cuvieri*, *Terebratula semiglobosa*, *Terebratulina gracilis*, *Echinoconus subrotundus*, &c. The lower 70 feet or so include the zone of *Inoceramus labiatus*, the next 90 or 100 feet that of *Terebratulina gracilis*, and the upper 50 or 60 feet, containing layers of black flints, that of *Holaster planus*. At the top comes the remarkably constant band of hard cream-coloured limestone known as the "Chalk Rock," varying from a few inches to 10 feet in thickness. Its upper surface is generally well defined, sometimes even suggestive of having been eroded, but it shades down into the Lower Chalk.[1]

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[1] W. Hill and A. J. Jukes-Browne, *Quart. Journ. Geol. Soc.* 1886, p. 216; *op. cit.* 1887, p. 580.

[2] Dr. J. Gwyn Jeffreys shows that the mollusca of the Chalk indicate comparatively shallow-water conditions; *Brit. Assoc. Rep.* 1877, Secs. p. 79. See also *Nature*, 3rd July 1884, p. 215; L. Cayeux, *Ann. Soc. Géol. Nord*, xix. (1891) pp. 95, 252. For a general account of the origin of the Chalk, with special reference to its minuter organisms, see T. R. Jones, *Trans. Hertford. Nat. Hist. Soc.* iii. part 5 (1885), p. 143.

[3] Jukes-Browne, *Geol. Mag.* 1880, p. 250.

[4] For an account of the Middle Chalk of Dover see W. Hill, *Quart. Journ. Geol. Soc.* 1886, p. 232.

Upper Chalk, Senonian[2] (*Upper Chalk with flints*).—This massive formation is composed of white, pulverulent, and usually tolerably pure chalk, with scattered flints, which, being arranged in the lines of deposit, serve to indicate the otherwise indistinct stratification of the mass. It has been generally regarded by English geologists as a single formation, with great uniformity of lithological characters and fossil contents. Mr. Whitaker, however, showed that distinct lithological platforms occur in it, and later researches, especially by MM. Hébert and Barrois, brought to light in it the same zones that occur in the Paris basin. Of these the lowest, or that of the Micrasters (Broadstairs and St. Margaret's Chalk), is most widely spread, the others having suffered most from denudation. It is well exposed along the cliffs of Kent at Dover, and also in the Isle of Thanet. At Margate its thickness has been ascertained by boring to be 265 feet. It contains two zones, in the lower of which the characteristic urchin is *Micraster cor-testudinarium*, while in the upper it is *M. cor-anguinum*. Near the top of the Micraster group of beds in the Isle of Thanet[3] lies a remarkable seam of flint about three or four inches thick, forming a nearly continuous floor, which has been traced southwards at the top of the cliffs between Deal and Dover. Again, on the coast of Sussex, what may be nearly the same horizon in the Chalk is defined by a corresponding band of massive flattened flints. The traces of emersion and erosion observed by M. Hébert in the Paris Chalk are regarded by Dr. Barrois as equally distinct on the English side of the Channel, in the form of surfaces of hardened and corroded chalk. One of these surfaces marks the upper limit of the Micraster group on the Sussex coast, where it consists of a band of yellowish, hardened, and corroded chalk about six inches thick, containing rolled green-coated nodules of chalk.[4] A similar hardened, corroded band forms the same limit in the Isle of Thanet. Among the fossils of the Micraster division the following may be mentioned: *Micraster cor-testudinarium, M. cor-anguinum, Cidaris clavigera, Echinocorys vulgaris, Echinoconus conicus, Epiaster gibbus, Terebratulina gracilis, Terebratula semiglobosa, Ostrea vesicularis, Inoceramus involutus.*

The middle subdivision, or Margate Chalk, has been named the Marsupite zone by Dr. Barrois, from the abundance of these crinoids. It attains a thickness of about 80 feet in the Isle of Thanet, where it contains few or no flints, and upwards of 400 feet in the Hampshire basin, where flints are numerous. Among its fossils are *Porosphæria globularis, Bourgueticrinus ellipticus, Marsupites ornatus, M. Milleri, Micraster cor-anguinum, Echinoconus conicus, Echinocorys vulgaris, Cidaris clavigera, C. sceptrifera, Thecidium Wetherelli, Terebratula semiglobosa, Rhynchonella plicatilis, Terebratulina striata, Spondylus* (*Lima*) *spinosus, S. dutempleanus, Pecten cretosus, Ostrea vesicularis, O. hippopodium, Inoceramus lingua* (and several others), *Belemnitella vera, B. Merceyi, Ammonites leptophyllus.*

The highest remaining group, or Norwich Chalk, forms the *Belemnitella* zone so well marked in northern Europe. It attains a thickness of from 100 to 160 feet in the Hampshire basin, is absent from that of London, but reappears in Norfolk, where it attains its greatest development. It is at Norwich a white crumbling chalk with layers of black flints. Among its fossils are *Parasmilia centralis, Trochosmilia laxa, Cyphosoma magnificum, Salenia geometrica, Echinocorys vulgaris, Rhynchonella octoplicata, R. limbata, Terebratula carnea, T. obesa, Ostrea lunata, Belemnitella mucronata, B. quadrata.*

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[1] Whitaker, *Mem. Geol. Surv.* iv. p. 46; Jukes-Browne, *Geol. Mag.* 1880, p. 254. A similar band occurs in Normandy.

[2] From Sens in the department of Yonne.

[3] F. A. Bedwell, *Geol. Mag.* 1874, p. 16.

[4] Barrois, 'Terrain Crétacé de l'Angleterre,' &c. 1876, p. 21.

The uppermost division, or Danian,[1] of the Continental Chalk appears to be absent in England, unless its lower portions are represented by some of the uppermost beds of the Norwich Chalk.

The Cretaceous system is sparingly represented in Ireland and Scotland. Under the Tertiary basaltic plateau of Antrim, there lies an interesting series of deposits which in lithological aspect differ greatly from their English equivalents, and yet from their fossil contents can be satisfactorily paralleled with the latter. They are thus arranged:[2]—

Hard white limestone	65	to 200 feet	= zone of Belemnitella mucronata.	Senonian.
,, ,,	13 ,,	16 ,,	,, Marsupites.	
Glauconitic (Chloritic) Chalk . . .	3 ,,	6½ ,,	,, Micrasters.	
Glauconitic (Chloritic) sand and sandstone .	3 ,,	16 ,,	,, Holaster planus. ,, Terebratulina gracilis.	Turonian.
Grey marls and yellow sandstones . .	3 ,,	30 ,,	,, Holaster subglobosus.	Cenomanian.
Glauconitic sand .	6 ,,	10 ,,	,, Pecten asper.	

In the west of Scotland, also, relics of the same type of Cretaceous formations have been preserved under the volcanic plateaux of Mull and Morven. They contain the following subdivisions in descending order:[3]—

White marly and sandy beds with thin seams of lignite	20 feet
Hard white chalk with *Belemnitella mucronata*, &c.	10 ,,
Thick white sandstones with carbonaceous matter	100 ,,
Glauconitic sands and shelly limestones, *Pecten asper*, *Exogyra conica*, *Janira quinquecostata*, *Nautilus deslongchampsianus*, &c. . .	60 ,,

France and Belgium.[4]—The Cretaceous system so extensively developed in western Europe is distributed in large basins, which, on the whole, correspond with those of the chief rivers. Thus in France, there are the basins of the Seine or of Paris, of the Loire or of Touraine, of the Rhone or of Provence, and of the Garonne or of Aquitania, including all the area up to the slopes of the Pyrenees. In most cases, these areas present such lithological and palæontological differences in their Cretaceous rocks as to indicate that they may have been to some extent even in Cretaceous times distinct basins of deposit.

A twofold subdivision of the system is followed in France, but with a difference of nomenclature and partly also of arrangement from that in use in England, as shown in the subjoined table:—

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[1] So named from its development in Denmark.

[2] Barrois, *op. cit.* p. 216. R. Tate, *Q. J. Geol. Soc.* xxi. p. 15.

[3] Judd, *Q. J. Geol. Soc.* xxxiv. p. 736.

[4] The Cretaceous system has been the subject of prolonged study by the geologists of France, and has given rise to considerable differences of nomenclature. The main subdivisions recognised and named by D'Orbigny have been generally adopted. But great diversity of opinion exists as to the names and limits of the lesser groups. There has been a tendency to excessive elaboration of subdivisions. The minor sections of the geological record must always be of but local significance, and it is to be regretted when they are treated as of any higher importance. M. Hébert refrained from burdening geological nomenclature with a long list of new names for local developments of strata, contenting himself with employing D'Orbigny's names for the formations or sections, and subdividing these into upper, middle, and lower stages. The student will find some of the rival systems of classification collected by Mr. Davidson, *Geol. Mag.* vi. (1869).

		SUB-STAGES.	N. FRANCE AND BELGIUM.	PROVENCE.
Cretace.	Danien.	Garumnien.[1]*	Calcaire pisolitique.	Calcaire à *Lychnus* de Rognac. Craie à lignites de Fuveau.
		Maestrichtien.[2]	Calcaire à Baculites du Cotentin. Craie de Ciply, Maestricht.	Calcaires marneux à *Hemipneustes.*
	Senonien.	Campanien.[3]	Craie de Meudon. Craie de Reims.	Calcaires à grands rudistes. Marnes et calc. à *Hippurites dilatatus.*
		Santonien.[4]	Craie à *Marsupites.* Craie à *Micr. cor-anguinum.* Craie à *M. cor-testudinarium.* Craie à *M. brevis.*	Calcaires à hippurites. Grès à échinides. Calcaires à hippurites. Gres à *Micraster brevis.* Couches à *Hippurites Zurcheri.*
	Turonien.	Angoumien.[5]	Craie à *Micr. breviporus* Craie à *Tereb. gracilis.*	Calc. à *Hippurites cornuvaccinum* et gres int. de Mornas. Calc. à *Biradiolites cornupastoris.* Gres d'Uchaux.
		Ligérien.[6]	Craie marneuse a *Inoceramus labiatus.*	Marnes à nucleolites. Calc. à *Amm. nodosoides.*
	Cenomanien.	Carentonien.[7]	Craie à *Belem. plena.* Couche fossilifere de Rouen. Tourtia de Mons.	Calc. a *Caprina adversa* et gres de Mondragon.
		Rothomagien.[8]	Craie glauconieuse a *Pecten asper. Amm.* (*Acanthoceras*) *Mantelli.* Gaize superieure du Bray.	Zone à *Anorthopygus orbicularis.* Zone a *Amm. Mantelli.*
Infra-cretacé.		JURA AND HAUTE MARNE.		
	Albien.[9]	Sables a *Amm. inflatus* (Vraconnien), Gaize de l'Argonne. Argiles, calcaires sables (*Amm. lautus, A. mamillaris*).		Calcaire glauconieux de Clansayes (*Desmoceras, Amm. inflatus*). Gres et calcaires de Clars à *Amm. Lyelli.*
	Aptien.[10]	Sables à *Amm. milletianus.* Calcaire, &c., à Plicatules.		Marnes a *Belem. semicanaliculatus.* Argiles à *Amm. Nisus.* Calcaire a *Ancyloceras Matheroni.* Calc. marneux à Plicatules.
	Urgonien.[11]	Marnes à Orbitolines et Calcaires a Pterocères et à *Requienia Lonsdalei* (Rhodanien). Calcaire à *Requienia ammonia.*		Calcaire à *Requienia Lonsdalei.* Calcaire à *Scaphites Yvani* et *Crioceras.*
	Néocomien.	Hauterivien.[12] (12 metres).	Calcaire jaune (Neuchâtel); Marnes et calc. à Spatangues. Marnes de Hauterive.	Calcaires à *Crioceras Duvali* et *Belemnites pistilliformis.* Marnes et Calcaires marneux à Ammonites ferrugineuses.
		Valenginien.[13] (50-130 metres).	Limonite de Métabief et calcaire roux à *Pygurus rostratus, Belemnites pistilliformis, B. dilatatus.* Calcaire à *Strombus Sautieri* (*Natica Leviathan*), *Nerinea gigantea.*	

For footnotes see next page.

From this table it will be perceived how marked a lithological difference is traceable between the Cretaceous deposits of the north and south of France. The northern area indeed is linked with that of England, and was evidently a part of the same great basin in which the English Cretaceous rocks were deposited. But in the south, the aspect of the rocks is entirely changed, and with this change there is so marked a difference in the accompanying organic remains as to indicate clearly the separation of the two regions in Cretaceous times.

INFRA-CRÉTACÉ.—Neocomian.[14]—This division is well seen in the eastern part of the Paris basin. The lowest dark marl, resting irregularly on the top of the Portlandian series, indicates the emersion of these rocks at the close of the Jurassic period. It is followed by ferruginous sands, calcareous blue marl, spatangus-limestones, and yellow marls (abounding in *Toxaster complanatus*, *Exogyra Couloni*, *Pterocera pelagi*, *Amm. radiatus*, &c.), the whole having a thickness of 125 to 140 feet, and representing chiefly the upper or Hauterivian sub-stage. Much more important is the development of the Neocomian deposits in the southern half of France. They present there evidence of deeper water at the time of their formation. The Neuchâtel type (p. 954) is prolonged into the northern part of Dauphiné, where it is seen in a group of limestones, with *Exogyra Couloni*, &c., in the lower, and *Toxaster complanatus*, &c., in the upper beds. Southwards the limestones are mostly replaced by marls, and the whole at Grenoble reaches a thickness of more than 1600 feet, resting on the upper Jurassic limestones, with *Terebratula diphyoides*.

Urgonian.—In the typical district of the lower valley of the Durance, this subdivision consists of massive limestones (1150 feet) with *Belemnites latus*, *B. dilatatus*, in the lower part; *Toxaster complanatus*, *Exogyra Couloni*, *Janira atava*, &c., in the central thickest portion; and *Toxaster ricordeanus*, *Ancyloceras*, *Crioceras*, &c., in the upper band. The Caprotina limestone of Orgon (whence the name of the type was taken) is a massive white rock, sometimes 1000 feet thick, marked by the abundance of its hippuritids, *Requienia* (*Caprotina*) *ammonia*, *R. Lonsdalei*, *R. gryphoides*, gigantic forms of *Nerinæa*, and corals. In the northern Cretaceous basin, the Urgonian stage appears as a series of sands and clays which in Haute Marne are from 60 to 80 feet thick, and contain *Toxaster ricordeanus*, &c.

Aptian.—In the typical district round Apt in Vaucluse, this stage consists of a lower group of blue marls (Marnes de Gargas), with *Plicatula placunea*, *Amm. Nisus*, *A. Dufrenoyi*, followed by a marly limestone with *Ancyloceras renauxianus*, *Ostrea aquila*. These beds swell out in the Bedoule to a thickness of 650 feet. One of their most distinctive characters is the prominence of the cephalopods of the *Ancyloceras* (*Crioceras*) type. In northern France the Aptian stage is chiefly clay, with *Plicatula placunea*, *P. radiola*, hence the name "Argile à Plicatules." Near St. Dizier, the lower beds are characterised by *Terebratula sella*, *Ostrea aquila*; the middle by *Amm. cornuelianus*, *Ancyloceras Matheroni*; the upper by *Amm. Nisus*, *A. Deshayesi*.

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[1] From the Haute Garonne, where the deposits are typically developed.

[2] Well seen at Maestricht.

[3] From Champagne.

[4] From Santonge.

[5] From Angoulême.

[6] From the basin of the Loire.

[7] From the Charente.

[8] From Rouen (*Rothomagus*).

[9] From the Department of the Aube.

[10] From Apt in Vaucluse.

[11] From Orgon, near Arles.

[12] From Hauterive, on the Lake of Neuchâtel (see p. 955).

[13] From the Château de Valengin, near Neuchâtel, Switzerland (see p. 954).

[14] See D'Archiac, *Mém. Soc. Géol. France*, 2^e^ sér. ii. p. 1; Raulin, *op. cit.* p. 219; Ebray, *Bull. Soc. Géol. France*, 2^e^ sér. xvi. p. 213; xix. p. 184; Cornuel, *Bull. Soc. Géol. France*, 2^e^ sér. xvii. p. 742; 3^e^ sér. ii. p. 371; Hébert, *op. cit.* 2^e^ sér. xxiv. p. 323; xxviii. p. 137; xxix. p. 394; Coquand, *op. cit.* xxiii. p. 561; Rouville, *op. cit.* xxix. p. 723; Bleicher, *op. cit.* 3^e^ sér. ii. p. 21; Toucas, *op. cit.* iv. p. 315.

Albian.[1]—In the eastern part of the Paris basin, this stage consists of a lower green pyritous sandy member (Sables verts), 30 feet thick, covered by an upper argillaceous band which represents the English Gault. These deposits continue the English type round the northern and eastern margin of the Paris basin. They have been found also in deep wells around Paris. In the valley of the Meuse and in the Ardennes, this stage consists of three subdivisions: (1) a lower green sand (*Amm. mamillaris*), with phosphatic nodules; (2) a brick clay with *Amm. lautus*, *A. tuberculatus*; (3) a porous calcareous and argillaceous sandstone known as *Gaize*, containing a large percentage of silica soluble in alkali (*Amm. inflatus*, &c.)

The English type of strata from the Weald upwards is also prolonged into France. Fresh-water sands and clays (with *Unio* and *Cyrena*), found above the Jurassic series in the Boulonnais, evidently represent the Weald, and are covered by dark green clays and sands (with *Ostrea aquila*), which are doubtless a continuation of the Folkestone beds, and by a thin blue clay which represents the Gault. Again, in the Pays de Bray, to the west of Beauvais, certain sands and clays resting on the Portlandian strata represent the Wealden series, and are followed by others which may be paralleled with the Urgonian, Albian, and Gault.[2]

In Belgium the Cretaceous system is underlain by certain clays, sands, and other deposits belonging to a continental period of older date than the submergence of that region beneath the sea in which were deposited the uppermost Neocomian beds. These scattered continental deposits have been grouped under the name of Aachenian.[3] That at least some part of them belongs to older Neocomian time, and may be coeval with the Weald, may be inferred from the remarkable discovery at Bernissart, already alluded to, where, in a buried system of Cretaceous ravines, the reptilian and ichthyic life of the time has been well preserved (*ante*, p. 931).

CRÉTACÉ.—The Upper Cretaceous rocks of France have been the subject of prolonged and detailed study by the geologists of that country.[4] The northern tracts form part of the Anglo-Parisian basin, in which the upper Cretaceous rocks of Belgium and England were laid down. The same palæontological characters, and even in great measure the same lithological composition, prevail over the whole of that wide area, which belongs to the northern Cretaceous province of Europe. Apparently only during the early part of the Cenomanian period, that of the Rouen Chalk, did the Anglo-Parisian basin communicate with the wider waters to the south, which were bays or gulfs freely opening to the main Atlantic. In these tracts a notably distinct type of Cretaceous deposits was accumulated, which, being that of the main ocean, covers a much larger geographical area and contains a much more widely diffused fauna than are presented by the more limited and isolated northern basin. There are few more striking contrasts between contemporaneously formed rocks in adjacent areas of deposit than that which meets the eye of the traveller who crosses from the basin of the Seine to those of the Loire and Garonne. In the north of France and Belgium, soft white chalk covers wide tracts, presenting the same lithological and scenic characters as in England. In the centre and south of France, the soft chalk is replaced by hard limestone, with comparatively few sandy or clayey beds. This mass of limestone attains its greatest development in the southern part of the department of the Dordogne, where it is said to be about 800 feet thick. The lithological differences, however, are not greater than those of the fossils. In the north of France, Belgium, and England, the singular molluscan family of the *Hippuritidæ* or *Rudistes* appears only occasionally and sporadically in the Cretaceous rocks, as if a stray individual had from time to time found its way into the region, but without being able to establish a colony there. In the south of France, however, the hippurites occur in prodigious quantity, often mainly composing the limestones, hence called hippurite limestone (Rudisten-Kalk). They attained a great size, and seem to have grown on extensive banks, like our modern oyster. They appear in successive species on the different stages of the Cretaceous system, and can be used for marking palæontological horizons, as the cephalopods are employed elsewhere. But while these lamellibranchs played so important a part throughout the Cretaceous period in the south of France, the numerous ammonites and belemnites, so characteristic of the Chalk in the Anglo-Parisian basin, were comparatively rare there. The very distinctive type of hippurite limestone has so much wider an extension than the northern or Chalk type of the upper Cretaceous system that it should be regarded as really the normal development. It ranges through the Alps into Dalmatia, and round the great Mediterranean basin far into Asia.

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[1] See, besides the works already cited, Barrois, *Bull. Soc. Géol. France*, 2^{e} sér, iii. 707; *Ann. Soc. Géol. du Nord*, ii. p. 1; Renevier, *Bull. Soc. Géol. France*, 2^{e} sér. ii. 704.

[2] Wealden deposits have been described as occurring even as far south as the province of Santander, Spain. A. Gonzalerz de Linares, *Anal. Soc. Esp. Hist. Nat.* vii. 487, 1878.

[3] On the Aachenian deposits see Dumont, 'Terrains Crétacés et Tertiaires' (edited by M. Mourlon, 1878), vol. i. pp. 11-52.

[4] Notably by MM. Hébert, Toucas, Coquand, and Cornuel. As already stated, considerable differences exist among French and Swiss geologists as to the nomenclature and the lines of demarcation between the upper Cretaceous formations, arising doubtless in great part from the varying aspect of the rocks themselves, according to the region in which they are studied. I have followed mainly M. Hébert, whose suggestive memoirs ought to be carefully read by the student. See especially his "Ondulations de la Craie dans le Bassin de Paris," *Bull. Soc. Géol. France* (2), xxix. (1872) p. 446; (3) iii. (1875) p. 512; and *Ann. Sci. Géol.* vii. (1876); "Description du Bassin d'Uchaux," *Ann. Sci. Géol.* vi. (1875); "Terrain Crétacé des Pyrénées," *Bull. Soc. Géol. France* (2), xxiv. (1867) p. 323; (3) ix. (1880) p. 62.

Cenomanian (Craie glauconieuse).—According to the classification of M. Hébert this stage is composed of two sub-stages: 1st, Lower or Rouen Chalk, equivalent to the Upper Greensand and Grey Chalk of England. In the northern region of France and Belgium this sub-stage consists of the following subdivisions: *a*, a lower assise of glauconitic beds like the English Upper Greensand, containing *Ammonites inflatus* below and *Pecten asper* above (Rothomagian sub-stage); *b*, Middle glauconitic chalk with *Turrilites tuberculatus*, *Holaster carinatus*. &c., probably equivalent to the English Glauconitic Marl and Chalk Marl; *c*, Upper hard, somewhat argillaceous, grey chalk with *Holaster subglobosus*; the threefold subdivision of this assise already given, is well developed in the north of France; *d*, Calcareous marls with *Belemnitella plena* (Carentonian sub-stage). 2nd, Upper or marine sandstone; according to M. Hébert this sub-stage is wanting in the northern region of France, England, and Belgium. In the old province of Maine it consists of sands and marls with *Anorthopygus orbicularis*, *Exogyra* (*Ostrea*) *columba*, *Trigonia*, and *Ostrea*. Farther south these strata are replaced by limestones with hippurites (*Caprina adversa*), which extend up into the Pyrenees and eastwards across the Rhone into Provence.[1]

Turonian (Craie marneuse).[2]—This stage presents a very different facies according to the part of the country where it is examined. In the northern basin, according to M. Hébert, only its lower portions occur, separated by a notable hiatus from the base of the Senonian stage, and consisting of marly chalk with *Inoceramus labiatus*, *I. Brongniarti*, *Ammonites nodosoides*, *A. peramplus*, *Terebratulina gracilis* (Ligerian sub-stage). He placed the zone of *Holaster planus* at the base of the Senonian stage, and believed that in the hiatus between it and the Turonian beds below, the greater part of the Turonian stage is really wanting in the north. On the other hand, Dr. Barrois and others would rather regard the zone of *Holaster planus* as the top of the Turonian stage (Angoumian sub-stage). In the north of France, as in England, it is a division of the White Chalk, containing *Ammonites peramplus, Scaphites Geinitzii, Spondylus spinosus, Inoceramus inæquivalvis, Terebratula semiglobosa, Holaster planus, Ventriculites moniliferus,* &c. Strata with *Inoceramus labiatus,* marking the base of the Turonian stage, can be traced through the south and south-east of France into Switzerland. These are overlain by marls, sandstones, and massive limestones with *Exogyra columba* and enormous numbers of hippurites (*Hippurites cornuvaccinum, Radiolites cornu-pastoris,* &c.) These hippurite limestones sweep across the centre of Europe and along both sides of the great Mediterranean basin into Asia, forming one of the most distinctive landmarks for the Cretaceous system.

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[1] See a memoir on the Upper Cretaceous Rocks of the basin of Uchaux (Provence by Hébert and Toucas, *Ann. Sciences Géol.* vi. (1875).

[2] For a review and parallelism of the Turonian, Senonian, and Danian stages in the north and south of Europe see Toucas, *Bull. Soc. Géol. France*, 3^{me} sér. x. (1882) p. 154; xi. p. 344; xix. p. 506; for a general description of the formations in the south-east of France, see Fallot, *Ann. Sci. Géol.* xviii. 1, 1885, and *Bull. Soc. Géol. France* (3), xiv. (1886) p. 1.

Senonian.—This stage is most fully developed in the northern basin, where it consists mainly of white chalk separable into the two divisions of: 1st, Micraster (Santonian) sub-stage composed of chalk beds, in the lower of which *Micraster cor-testudinarium,* and in the upper *M. cor-anguinum* is the prevalent urchin. The same palæontological facies occurs in this and the other group as in the corresponding strata of England already described. 2nd, Belemnitella (Campanian) sub-stage, with *B. quadrata* in a lower zone, and *B. mucronata* (Meudon Chalk) in a higher. In the south and south-east of France the corresponding beds consist of limestones, sandstones, and marls, with abundant hippurites, and also include some fresh-water deposits and beds of lignite.

Danian.—This subdivision of the Cretaceous system is specially developed in the northern basin. In the Cotentin, a limestone with *Baculites anceps, Scaphites constrictus,* and other fossils has been paralleled with the Maestricht Chalk (Maestrichtian sub-stage). In the neighbourhood of Paris and in the department of Oise and Marne, a rock long known as the Pisolitic Limestone occurs in patches, lying unconformably on the White Chalk (Garumnian sub-stage). The long interval which must have elapsed between the highest Senonian beds and this limestone is indicated not only by the evidence of great erosion of the chalk previous to the deposit of the limestone, but also by the marked palæontological break between the two rocks. The general aspect of the fossils resembles that of the older Tertiary formations, but among them are some undoubted Cretaceous species. In the south-east of Belgium, the Danian stage is well exposed, resting unconformably on a denuded surface of chalk. In Hainault, it consists of successive bands of yellowish or greyish chalk, between some of which there are surfaces of denudation, with perforations of boring mollusks, so that it contains the records of a prolonged period (Chalk of St. Vaast, Obourg, Nouvelles, Spienne, and Ciply). Among the fossils are *Belemnitella mucronata, Baculites Faujasii, Nautilus DeKayi* (but no *Ammonites, Hamites,* or *Turrilites*), *Inoceramus Cuvieri, Ostrea flabelliformis, O. lateralis, O. vesicularis, Crania ignabergensis, Terebratulina striata, Fissurirostra Palissii* (characteristic), *Radiolites ciplyanus, Eschara* several species and in great numbers, *Echinocorys vulgatus, Holaster granulosus.* The well-known chalk of Maestricht is equivalent to part of these strata, but appears to embrace also a higher horizon containing *Hemipneustes striato-radiatus, Crania ignabergensis, Terebratulina striata, Fissurirostra pectiniformis, Ostrea lunata, O. vesicularis, Janira quadricostata,* and numerous remains of *Mosasaurus* and of chelonians, together with *Voluta fasciolaria,* and other characteristically Tertiary genera of mollusks.[1] Similar strata and fossils occur at Faxoe, Denmark, and in the south of Sweden.[2] The terrestrial flora in the highest Cretaceous series at Aix-la-Chapelle has been already referred to (p. 922).

The Danian stage is likewise represented in the south of France in some strongly contrasted forms. Towards the west it consists of marly, chloritic, and compact limestones (about 650 feet thick) with a marine fauna, including *Nautilus danicus*, *Ananchytes*, *Micraster tercensis*, &c. Eastwards, however, in Provence there is evidence of a gradual shallowing of the Upper Cretaceous sea in Cenomanian and Turonian time, until that area had become a fluviatile or lacustrine tract, in which during the later stages of the Cretaceous period a mass of fresh-water strata more that 2600 feet thick was accumulated. This enormous development of strata consists of limestones, marls, and lignites.

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[1] Dumont, 'Mém. Terrains Crétacés,' &c. 1878; Mourlon, 'Géol. de la Belgique,' 1880.

[2] Hébert, *Bull. Soc. Géol. France* (3), v. 645; Lundgren, *op. cit.* x. (1882) p. 456.

Germany.—The Cretaceous deposits of Germany, Denmark, and the south of Sweden were accumulated in the same northern province with those of Britain, the north of France, and Belgium, for they present on the whole the same palæontological succession, and even to a considerable extent the same lithological characters. It would appear that the western part of this region began to subside before the eastern, and attained a greater amount of depression beneath the sea. In proof of this statement, it may be mentioned that the Neocomian clays of the north of England extend as far as the Teutoburger Wald, but are absent from the base of the Cretaceous system in Saxony and Bohemia. In north-west Germany, Neocomian strata, under the name of Hils, appear at many points between the Isle of Heligoland (where representatives of part of the Speeton Clay and the Hunstanton Red Chalk occur) and the east of Brunswick, indicative of what was, doubtless, originally a continuous deposit. In Hanover, they consist of a lower series of conglomerates (Hils-conglomerat), and an upper group of clays (Hils-thon). Appearing on the flanks of the hills which rise out of the great drift-covered plains, they attain their completest development in Brunswick, where they attain a total thickness of 450 feet, and consist of a lower group of limestone and sandy marls, with *Toxaster complanatus*, *Exogyra Couloni* (*sinuata*), *Ammonites bidichotomus*, *A. astierianus*, and many other fossils ; a middle group of dark blue clays with *Belemnites brunsvicensis*, *Ammonites Nisus*, *Crioceras* (*Ancyloceras*) *Emerici*, *Exogyra Couloni* (*sinuata*), &c., and an upper group of dark and whitish marly clays with *Ammonites Martini*, *A. Deshayesi*, *A. Nisus*, *Belemnites Ewaldi*, *Toxoceras royerianum*, *Crioceras*, &c.[1] Below the Hils-thon in Westphalia, the Harz, and Hanover, the lower parts of the true marine Neocomian series are replaced by a massive fluviatile formation corresponding to the English Wealden, and divisible into two groups : 1st, Deister sandstone (150 feet), like the Hastings Sand of England, consisting of fine light yellow or grey sandstone (forming a good building material), dark shales, and seams of coal varying from mere partings up to workable seams of three, and even more than six, feet in thickness. These strata are full of remains of terrestrial vegetation (*Equisetum*, *Baiera*, *Oleandridium*, *Lacopteris*, *Sagenopteris*, *Anomozamites*, *Pterophyllum*, *Podozamites*, and a few conifers), also shells of fresh-water genera (*Cyrena*, *Paludina*), cyprids, and remains of *Lepidotus* and other fishes; 2nd, Weald Clay (65-100 feet) with thin layers of sandy limestone (*Cyrena*, *Unio*, *Paludina*, *Melania*, *Cypris*, &c.)[2] The Gault (Aptian and Albian) of north-western Germany contains three groups of strata. The lowest of these consists of blue clays with *Belemnites brunsvicensis*, *Amm.* (*Acanthoceras*) *Martini*, *A.* (*Hoplites*) *Deshayesi*, followed by white marl with *Belem. Ewaldi*. The middle consists of a lower clay with the zone of *Ammonites* (*Acanthoceras*) *milletianus*.

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[1] A. von Strombeck, *Zeitsch. Deutsch. Geol. Ges.* i. p. 462 ; xii. 20 ; *N. Jahrb.* 1855, pp. 159, 644 ; Judd, *Q. J. Geol. Soc.* xxvi. p. 343 ; Vacek, *Jahrb. Geol. Reichsanst.* 1880, p. 493.

[2] W. Dunker, 'Ueber den norddeutsch. Walderthon, u. s. w.,' Cassel, 1844 ; Dunker and Von Meyer, 'Monographie der norddeutsch. Walderbildung, u. s. w.,' Brunswick, 1846 ; Heinrich Credner, 'Ueber die Gliederung der oberen Jura und der Wealdenbildung in nordwestlichen Deutschland,' Prague, 1863 ; C. Struckmann, 'Die Wealden-Bildungen der Umgegend von Hannover,' 1880 ; A. Schenk on the Wealden Flora of North Germany, *Palæontographica*, xix. xxiii.

and an upper clay with *Amm.* (*Hoplites*) *tardefurcatus.* The highest contains at its base a clay with *Belemnites minimus*, and at its top the widely diffused and characteristic "Flammenmergel"—a pale clay with dark flame-like streaks, containing the zone of *Ammonites* (*Schlönbachia*) *inflatus*, *Amm.* (*Hoplites*) *lautus*, &c.[1] In the Teutoburger Wald the Gault becomes a sandstone.

The Upper Cretaceous rocks of Germany present the greatest lithological contrasts to those of France and England, yet they contain so large a proportion of the same fossils as to show that they belong to the same period, and the same area of deposit.[2] The Cenomanian stage consists in Hanover of earthy limestones and marls (Planer), which traced southward are replaced in Saxony and Bohemia by glauconitic sandstones (Unter-Quader) and limestone (Unter-Planerkalk). The lowest parts of the formation in the Saxon, Bohemian, and Moravian areas are marked by the occurrence in them of clays, shales, and even thin seams of coal (Pflanzen-Quader), containing abundant remains of a terrestrial vegetation which possesses great interest, as it contains the oldest known forms of hard-wood trees (willow, ash, elm, laurel, &c.) The Turonian beds, traced eastwards, from their chalky and marly condition in the Anglo-Parisian Cretaceous basin, change in character, until in Saxony and Bohemia they consist of massive sandstones (Mittel-Quader) with limestones and marls (Mittel-Planer). In these strata, the occurrence of such fossils as *Inoceramus labiatus*, *I. Brongniarti*, *Ammonites peramplus*, *Scaphites Geinitzii*, *Spondylus* (*Lima*) *spinosus*, *Terebratula semiglobosa*, &c., shows their relation to the Turonian stage of the west. The Senonian[3] stage presents a yet more extraordinary variation in its eastern prolongation. The soft upper Chalk of England, France, and Belgium, traced into Westphalia, passes into sands, sandstones, and calcareous marls, the sandy strata increasing southwards till they assume the gigantic dimensions which they present in the gorge of the Elbe and throughout the picturesque region known as Saxon Switzerland (Ober-Quader). The horizon of these strata is well shown by such fossils as *Belemnitella quadrata*, *B. mucronata*, *Nautilus danicus*, *Marsupites ornatus*, *Bourgueticrinus ellipticus*, *Crania ignabergensis*, &c.

At Aix-la-Chapelle an exceedingly interesting development of Upper Cretaceous rocks is exposed. These strata, referable to the Senonian stage, consist of a lower group of sands with *Belemnitella quadrata* and abundant remains of terrestrial vegetation (p. 922),[4] and an upper group of marl and marly chalk with *Belemnitella mucronata*, *Gryphæa vesicularis*, *Crania ignabergensis*, *Mosasaurus*, &c.

Switzerland and the Chain of the Alps.[5]—This area is included in the southern basin of deposit. In the Jura, and especially round Neuchâtel, the Neocomian beds are typically developed. This stage and its two sub-stages have received their names from localities in that region where they are best seen (pp. 948, 949). (1)

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[1] *Geol. Mag.* vi. (1869) p. 261. A. von Strombeck, *Zeitsch. Deutsch. Geol. Ges.* xlii. (1890) p. 557.

[2] On the distribution of the Cephalopods in the Upper Cretaceous rocks of north Germany, see C. Schluter, *Zeitsch. Deutsch. Geol. Ges.* xxviii. p. 457 (see *Geol. Mag.* 1877, p. 169), and *Palæontographica*, xxiv. 123-263, 1876. For the *Inocerami*, *Zeitsch. Deutsch. Geol. Ges.* xxix. p. 735.

[3] German geologists commence the Senonian with the zone of *Belemnitella quadrata*, the upper Senonian of Hébert.

[4] For a list of these plants see H. von Dechen, 'Geol. Paläont. Übersicht der Rheinprovinz,' &c. 1884, p. 427.

[5] Studer's 'Geologie der Schweiz'; Gümbel, 'Geognostische Beschreib. Bayer. Alpen,' vol. i. p. 517 *et seq.*; 'Geognostische Beschreib. des Ostbayer. Grenzegebirg,' 1868, p. 697; Jules Marcou, *Mém. Soc. Géol. France* (2), iii.; P. de Loriol, 'Invertébrés de l'Étage Néocomien moyen du Mt. Salève,' Geneva, 1861; Renevier, *Bull. Soc. Géol. France* (3), iii.; A. Favre, *ibid.*; Von Hauer's 'Die Geologie der Oesterr. Ungar. Monarchie,' 1878, p. 505 *et seq.* E. Fraas, 'Scenerie der Alpen.'

Valenginian—a group of limestones and marls (130-260 feet) with *Toxaster Campichei*, *Pygurus rostratus*, *Strombus Sautieri* (*Natica Leviathan*), *Cidaris hirsuta*, *Belemnites pistilliformis*, *B. dilatatus*, *Ammonites* (*Oxynoticeras*) *gevrilianum*, &c.; (2) Hauterivian —a mass of blue marls surmounted by yellowish limestones, the whole having a thickness that varies up to 250 feet; *Toxaster complanatus*, *Exogyra Couloni*, *Janira atava*, *Perna Mulleti*, *Nautilus pseudo-elegans*, *Amm.* (*Hoplites*) *radiatus*, *Amm.* (*Holcostephanus*) *astierianus*, &c. The Aptian and Albian stages (Gault) are recognisable in a thin band of greenish sandstone and marls which have long been known for their numerous fossils (Perte du Rhone, St. Croix).

In the Alpine region, the Neocomian formation is represented by several hundred feet of marls and limestones, which form a conspicuous band in the mountainous range separating Berne from Wallis, and thence into eastern Switzerland and the Austrian Alps (Spatangenkalk). Some of these massive limestones are full of hippurites of the *Caprina* group (Caprotinenkalk, with *Requienia* (*Caprotina*) *Lonsdalei*, *Radiolites neocomiensis*, &c.), others abound in polyzoa (Bryozoenkalk), others in foraminifera (Orbitolitenkalk). The Aptian and Albian stages traceable in the Swiss Jura can also be followed into the Alps of Savoy. In the Vorarlberg and Bavarian Alps their place is taken by calcareous glauconite beds and the Turrilite greensand (*T. Bergeri*); but in the eastern Alps they have not been recognised. The lowest portions of the massive *Caprotina* limestone (Schrattenkalk) are believed to be Neocomian, but the higher parts are Upper Cretaceous.

One of the most remarkable formations of the Alpine regions is the enormous mass of sandstone which, under the name of Flysch and Vienna Sandstone, stretches from the south-west of Switzerland through the northern zone of the mountains to the plains of the Danube at Vienna. Fossils are exceedingly rare in this rock, the most frequent being fucoids, which afford no clue to the geological age of their enclosing strata. That the older portions in the eastern Alps are Cretaceous, however, is indicated by the occurrence in them of occasional *Inocerami*, and by their interstratification with true Neocomian limestone (Aptychenkalk). The definite subdivisions of the Anglo-Parisian Upper Cretaceous rocks cannot be applied to the structure of the Alps, where the formations are of a massive and usually calcareous nature. In the Vorarlberg, they consist of massive limestones (Seewenkalk) and marls (Seewenmergel), with *Ammonites Mantelli*, *Turrilites costatus*, *Inoceramus striatus*, *Holaster carinatus*, &c. In the north-eastern Alps, they present the remarkable facies of the Gosau beds, which consist of a variable and locally developed group of marine marls, sandstones, and limestones, with occasional intercalations of coal-bearing fresh-water beds. These strata rest unconformably on all rocks more ancient than themselves, even on older Cretaceous groups. They have yielded about 500 species of fossils, of which only about 120 are found outside the Alpine region, chiefly in Turonian, partly in Senonian strata. Much discussion and a copious literature has been devoted to the history of these deposits.[1] The loosely imbedded shells suggested a Tertiary age for the strata; but their banks of corals, sheets of orbitolite- and hippurite-limestone and beds of marl with *Ammonites*, *Inocerami* and other truly Cretaceous forms, have left no doubt as to their really Upper Cretaceous age. Among their subdivisions, the zone of *Hippurites cornu-vaccinum* is recognisable. From some lacustrine beds of this age, near Wiener Neustadt, a large collection of reptilian remains has been obtained, including deinosaurs, chelonians, a crocodile, a lizard, and a pterodactyle—in all fourteen genera and eighteen species.[1] Probably more or less equivalent to the Gosau beds are the massive hippurite-limestones and certain marls, containing *Belemnitella mucronata*, *Echinocorys vulgaris*, &c., of the Salzkammergut and Bavarian Alps.[2] The Upper Cretaceous rocks of the south-eastern Alps are distinguished by their hippurite-limestones (Rudistenkalk) with shells of the *Hippurites* and *Radiolites* groups, while the Lower Cretaceous limestones are marked by those of the *Caprina* group. They form ranges of bare white, rocky, treeless mountains, perforated with tunnels and passages (Dolinen, p. 367). In the southern Alps white and reddish limestones (Scaglia) have a wide extension.

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[1] See among other memoirs, Sedgwick and Murchison, *Trans. Geol. Soc.* 2nd ser. iii.; Reuss, *Denkschrift. Akad. Wien*, vii. 1; *Sitzb. Akad. Wien*, xi. 882; Stoliczka, *Sitzb. Akad. Wien*, xxviii. 482; lii. 1; Zekeli, *Abhandl. Geol. Reichsanst. Wien*, i. 1 (Gasteropods); F. von Hauer, *Sitzb. Akad. Wien*, liii. 300 (Cephalopods); 'Palæont. Oesterreich,' i. 7; 'Geologie,' p. 516; Zittel, *Denkschrift. Akad. Wien*, xxiv. 105; xxv. 77 (Bivalves); Bünzel, *Abhandl. Geol. Reichsanst.* v. 1; Gumbel, 'Geognostische Beschreib. Bayerisch. Alpen,' 1861, p. 517 *et seq.* Redtenbacker, *Abhandl. Geol. Reichsanst.* v. (Cephalopods).

Basin of the Mediterranean.—The southern type of the Cretaceous system attains a great development on both sides of the Mediterranean basin. The hippurite (*Caprotina*) limestones of Southern France and the Alps are prolonged into Italy and Greece, whence they range into Asia Minor and into Asia.[3] Cretaceous formations of the same type appear likewise in Portugal, Spain, and Sicily, and cover a vast area in the north of Africa. In the desert region south of Algiers, they extend as wide plateaux with sinuous lines of terraced escarpments.[4]

Russia.—The Cretaceous formations, which are well developed in the range of the Carpathian mountains, sink below the Tertiary deposits in the plains of the Dniester, and rise again over a vast region drained by the Donetz and the Don. They have been studied in central and eastern Russia by the officers of the Russian Geological Survey, who have pointed out the remarkable resemblance between their organic remains and those of the Anglo-French region. There is in particular a close parallelism between them and the English Speeton Clay in their intimate relationship to the Jurassic system below. The Volga group already (p. 919) referred to is succeeded by typical Neocomian deposits, which are well developed in the district of Simbirsk along the Volga, where they consist of dark clays with sandy layers and phosphatic concretions, divisible into three horizons. The lowest of these yields pyritous ammonites, especially *Amm.* (*Holcostephanus*) *versicolor*, *A.* (*Holcost.*) *inversus*, also *Belemnites pseudopanderianus*, *Astarte porrecta*. The middle zone contains septaria enclosing *Amm.* (*Holcost.*) *Decheni*, *umbonatus*, *progredicus*, *fasciatofalcatus*, *discofalcatus*, *Barboti*, *Inoceramus aucella*, *Rhynchonella obliterata*. The highest zone is almost unfossiliferous near Simbirsk, but its lower layers yield *Pecten crassitesta*. Deposits of the same type as the Anglo-French Aptian are well developed in the governments of Simbirsk and Saratov, and are characterised by *Amm.* (*Hoplites*) *Deshayesi* and *A.* (*Amaltheus*) *bicurvatus*. The Albian or Gault, which is found in the government of Moscow, and may eventually be traced over a wide area, has yielded a number of ammonites, especially of the genus *Hoplites* (*H. dentatus*, *talitzianus*, *Bennettiæ*, *Engersi*, *Tethydis*, *jachromensis*, *Dutemplei*, *Haploceras Beudanti*). This stage is well developed in the Caucasus, Transcaucasia, and the trans-Caspian region. In the chief Russian Cretaceous area the Cenomanian stage begins with dark clay closely related to the underlying Jurassic series, from the denudation and rearrangement of which it may have been derived. The clay shades upward into sandy, glauconitic, and phosphatic deposits, which gradually assume the condition of chalky marls. These Cenomanian strata appear to have a wide extent at the base of the Upper Cretaceous formations of central Russia. They contain numerous remains of fishes (*Ptychodus, Lamna, Odontaspis, Otodus*) with bones of ichthyosaurs and plesiosaurs. Ammonites are rare, but *Amm.* (*Schlönbachia*) *varians* occurs, also *Belemnitella plena, Exogyra haliotidea, E. conica, Ostrea hippopodium, Janira* (*Vola*) *quinquecostata, Pecten laminosus, Rhynchonella nuciformis*, &c. Turonian strata have likewise been found over a wide tract in central Russia. The lower bands with *Inoceramus* (*I. russiensis, labiatus, Brongniarti, lobatus* aff.) abundant, *Belemnitella* and *Ostrea vesicularis* are of constant occurrence in the Cretaceous region of central Russia. In that area, however, the Senonian and higher Cretaceous stages are not well developed, though they assume greater importance in the southern part of the Empire.[1]

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[1] Seeley, *Q. J. Geol. Soc.* 1881, p. 620.

[2] See, for this region, Gumbel, who gives a table of correlations for the European Cretaceous rocks with those of Bavaria. 'Geognost. Beschreib. Ostbayer. Grenzgeb.' pp. 700, 701.

[3] For an account of Syrian Cretaceous fossils see R. P. Whitfield, *Bull. Amer. Mus. Nat. Hist.* iii. (1891) p. 381.

[4] Coquand, 'Description géol. et paléontol de la région sud de la province de Constantin,' 1862; Rolland, *Bull. Soc. Géol. France* (3) ix. 508; Péron, *op. cit.* p. 436; this author has published a valuable memoir on the Geology of Algeria, with a full bibliography, *Ann. Sciences Géol.* 1883; Zittel, 'Beiträge zur Geologie der Libyschen Wüste,' 1883.

India.—The hippurite limestone of south-eastern Europe is prolonged into Asia Minor, and occupies a vast area in Persia. It has been detected here and there among the Himalaya Mountains in fragmentary outliers. Southward of these marine strata, there appears to have existed in Cretaceous times a wide tract of land, corresponding on the whole with the present area of the Indian peninsula, but not improbably stretching south-westwards so as to unite with Africa. On the south-eastern side of this area the Cretaceous sea extended, for near Trichinopoly and Pondicherry a series of marine deposits occurs, corresponding to the European Upper Cretaceous formations, with which it has 16 per cent of fossil species in common. Among these are *Amm.* (*Acanthoc.*) *rhotomagensis, A.* (*Pachydiscus*) *peramplus*, and *Rhynchonella compressa*. The occurrence of *Nautilus danicus* in the higher sands of Ninnyur probably shows that the Cretaceous system of India reaches as high as the Danian stage.[2] Similar strata with many of the same fossils appear on the African coast in Natal. The most remarkable episode of Cretaceous times in the Indian area was undoubtedly the colossal outpouring of the Deccan basalts (p. 259). These rocks, lying in horizontal or nearly horizontal sheets, attain a vertical thickness of from 4000 to 6000 feet or more. They cover an area estimated at 200,000 square miles, though their limits have no doubt been reduced by denudation. Their oldest portions lie slightly unconformably on Cenomanian rocks, and in some places appear to be regularly interstratified with the uppermost Cretaceous strata. The occurrence of remains of fresh-water mollusks, land-plants, and insects, both in the lowest and highest parts of the volcanic series, proves that the lavas must have been subaerial. This is one of the most gigantic outpourings of volcanic matter in the world.[3]

North America.—The Cretaceous system stretches over a vast portion of the American continent, and sometimes reaches an enormous thickness. Sparingly developed in the eastern States, from New Jersey into South Carolina, it there includes the younger or Neocomian plant-bearing strata of Virginia. It spreads out over a wide area in the south, stretching round the end of the long Palæozoic ridge from Georgia through Alabama and Tennessee to the Ohio; and reappearing from under the Tertiary formations on the west side of the Mississippi over a large space in Texas and the south-west. Its greatest development is reached in the Western States and Territories of the Rocky Mountain region, Wyoming, Utah, and Colorado, whence it ranges northward into British America, covering thousands of square miles of the prairie country between Manitoba and the Rocky Mountains, and extending westwards even as far as Queen Charlotte Islands, where it is well developed. It has a prodigious northward extension, for it has been detected in Arctic America near the mouth of the Mackenzie River, and in northern Greenland.

The Cretaceous clays and greensand marls of New Jersey have yielded a tolerably ample molluscan fauna, comprising species of *Terebratula*, *Terebratella*, *Terebratulina*, *Ostrea*, *Gryphæa*, *Exogyra*, *Anomia*, *Pecten*, *Amusium*, *Spondylus*, *Plicatula*, *Mytilus*, *Modiola*, *Inoceramus*, *Trigonia*, *Unio*, *Cardita*, *Crassatella*, *Cardium*, and many other genera.[1] Towards the south over the site of Texas, the Cretaceous sea appears to have been deeper and clearer than elsewhere in the American region, for its presence is recorded chiefly by limestones, among which occur abundant hippurites (*Caprotina*, *Caprina*) and foraminifera (*Orbitolites*).[2] Northwards the strata are chiefly sandy, and present alternations of marine and terrestrial conditions, pointing to oscillations which especially affected the Rocky Mountain and western regions. The greatest development of the system is to be seen in the north of Utah and in Wyoming, where it presents a continuous series of deposits unbroken by any unconformability for a thickness of from 11,000 to 13,000 feet. The following table shows the character of these deposits in descending order :—

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[1] Nikitin, 'Les Vestiges de la periode Crétacée dans la Russie centrale,' *Mem. Com. Géol. Russe*, v. No. 2 (1888) p. 165.

[2] J. Seunes, *Mem. Soc. Géol. France, Paléont.* t. ii. fasc. iii. (1891) p. 22.

[3] Medlicott and Blanford, 'Geology of India,' see *ante*, pp. 259, 592. The Upper Cretaceous fauna of India is described in *Palæontograph. Indica*, ser. xiv. (1883).

Laramie (Lignitic) group.—Buff and grey sandstones, with bands of dark clays and numerous coal-seams, containing abundant terrestrial vegetation of Tertiary types, land and fresh-water mollusks (*Unio*, *Limnæa*, *Planorbis*, *Helix*, *Pupa*, &c.), and remains of fishes (*Beryx*, *Lepidotus*), turtles (*Trionyx*, *Emys*, *Compsemys*), and reptiles (*Crocodilus*, *Agathaumus*, &c.). This group is by some geologists placed among the Tertiary systems, or as a passage series between the Cretaceous and Eocene systems (see p. 982). Thickness in Green River basin 5000 feet.

On this horizon come the "Ceratops beds" of Wyoming, 3000 feet thick, which rest directly upon the Fox Hills group. They consist of alternating sandstones, shales, and lignites, and are remarkable for the extraordinary number and wonderful preservation of the deinosaurs, mammals, and other forms which they have yielded.[3]

Fox Hills group.—Grey, rusty, and buff sandstones, with numerous beds of coal and interstratifications containing a varied assemblage of marine shells (*Belemnitella*, *Nautilus*, *Ammonites*, *Baculites*, *Mosasaurus*, &c.) Thickness on the great plains 1500 feet, which in the Green River basin expands to from 3000 to 4000 feet.

Colorado group.—Calcareous shales and clays with a central sandy series, and, in the Wahsatch region, seams of coal as well as fluviatile and marine shells. Thickness east of the Rocky Mountains 800 to 1000 feet, but westwards in the region of the Uinta and Wahsatch Mountains 2000 feet. This group was proposed and named by Hayden and Clarence King to include the following sub-groups in the original classification of Messrs. Meek and Hayden in the Missouri region :—

Fort Pierre sub-group.—Carbonaceous shales, marls, and clays (*Inoceramus Barabini*, *Baculites ovatus*, *Scaphites nodosus*, *Ammonites*, *Ostrea congesta*, &c.)

Niobrara sub-group.—Chalky marls and bituminous limestones (*Baculites*, *Inoceramus deformis*, *I. problematicus*, *Ostrea congesta*, fish remains).

Fort Benton sub-group.—Shales, clays, and limestones (*Scaphites warrenensis*, *Ammonites*, *Prionocyclas Woolgari*, *Ostrea congesta*).

Dakota group, composed of a persistent basal conglomerate (which is 200 feet thick and very coarse in the Wahsatch region) overlain with yellow and grey massive sandstones, sometimes with clays and seams of coal or lignite (dicotyledonous leaves in great numbers, *Inoceramus*, *Cardium*, &c.) Thickness 400 feet and upwards.[4]

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[1] R. P. Whitfield, *Monogr. U.S. Geol. Surv.* vol. ix. (1885).

[2] For fossils see 'List of Invertebrate Fossils from the Cretaceous Formations of Texas,' R. T. Hill, Austin, Texas, 1889.

[3] J. B. Hatcher, *Amer. Journ. Sci.* xlv. (1893) p. 135.

[4] Hayden's *Reports of Geographical and Geological Surveys of Western Territories*; King's *Geological Report of Exploration of 40th Parallel*, vol. i.; G. H. Eldridge, *Amer. Journ. Sci.* xxxviii. (1889) p. 313. J. J. Stevenson, *Amer. Geologist*, 1889, p. 391.

The extraordinary palæontological richness of these western Cretaceous deposits has been already referred to. They contain the earliest dicotyledonous plants yet found on this continent, upwards of 100 species having been named, of which one-half were allied to living American forms. Among them are species of oak, willow, poplar, beech, elm, dogwood, maple, hickory, fig, cinnamon, laurel, smilax, tulip-tree, sassafras. sequoia, American palm (*Sabal*), and cycads.[1] The more characteristic marine mollusca are species of *Terebratula*, *Ostrea*, *Gryphæa*, *Exogyra*, *Inoceramus*, *Hippurites*, *Radiolites*, *Ammonites*, *Scaphites*, *Hamites*, *Baculites*, *Belemnites*, *Ancyloceras*, and *Turrilites*. Of the fishes of the Cretaceous sea, many species are known, comprising large predaceous representatives of modern or osseous types like the salmon and saury, though cestracionts and ganoids still flourished. But the most remarkable feature in the organic contents of these beds is the extraordinary number and variety of the reptilian remains, to which reference has been already made (p. 931). Some of the early types of toothed birds also have been obtained from the same important strata (p. 935).

No question in American geology has given rise to more controversy than the place which should be assigned to the Laramie or Lignitic group, whether in the Cretaceous or Tertiary series.[2] The group consists mainly of lacustrine strata, with occasional brackish-water bands. Somewhere about 140 species of mollusks have been obtained from them which are terrestrial or fresh-water forms, with a few that may be brackish-water. They include numerous species of *Ostrea*, *Anomia*, *Unio*, *Corbicula*, *Corbula*, *Limnæa*, *Planorbis*, *Physa*, *Helix*, *Pupa*, *Goniobasis*, *Hydrobia*, and *Viviparus*.[3] The abundant terrestrial flora resembles in many respects the present flora of North America. A few of the plants are common to the Middle Tertiary flora of Europe, and a number of them have been met with in the Tertiary beds of the Arctic regions. Some of the seams of vegetable matter are true bituminous coals and even anthracites. According to Cope, the vertebrate remains of the Laramie group bind it indissolubly to the Mesozoic formations. Lesquereux, on the other hand, has insisted that the vegetation is unequivocally Tertiary. The former opinion has been maintained by Clarence King, Marsh, and others; the latter by Hayden and his associates in the Survey of the Western Territories. Cope, admitting the force of the evidence furnished by the fossil plants, concludes that "there is no alternative but to accept the result that a Tertiary flora was contemporaneous with a Cretaceous fauna, establishing an uninterrupted succession of life across what is generally regarded as one of the greatest breaks in geologic time." The vegetation had apparently advanced more than the fauna in its progress towards modern types.[4] The Laramie group was disturbed along the Rocky Mountain region before the deposition of the succeeding Tertiary formations, for these lie unconformably upon it. So great have been the changes in some regions, that the strata have assumed the character of hard slates like those of Palæozoic date, if indeed they have not become in California thoroughly crystalline masses. The same mingled marine and terrestrial type of Cretaceous rocks can be followed into California, where the higher parts of the series contain beds of coal. The coast ranges are described by Whitney as largely composed of Cretaceous rocks, usually somewhat metamorphic and sometimes highly so.[1] In the foot-hills, on the eastern slopes of the Rocky Mountains, near the United States and Canadian boundary, the beds are comparatively undisturbed and the coal is bituminous; within the Rocky Mountain area the strata are greatly contorted and the coal is there anthracitic.

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[1] For an account of the Laramie Flora see L. F. Ward, *6th Ann. Rep. U.S. Geol. Surv.* 1885, p. 405. *Bull. U.S. Geol. Surv.* No. 37 (1887).

[2] For a *résumé* of the progress of opinion on this subject see Ward, *6th Ann. Rep. U.S. Geol. Surv.* 1885, p. 406.

[3] C. A. White, "A Review of the Non-Marine Fossil Mollusca of North America," *3rd U.S. Geol. Survey Report*, 1883; *Bull. U.S. Geol. Surv.* No. 34, 1886. See the same author's paper on the mingling of an ancient fauna and modern flora in these deposits, *Amer. Journ. Sci.* (3) xxvi. p. 120.

[4] See remarks *ante*, pp. 660, 668. Neumayr (*N. Jahrb.* 1884, i. p. 74) makes a comparison between the Laramie group and the inter-trappean beds of the Deccan.

The blending of marine and terrestrial formations, so conspicuous in the Western Territories of the American Union, can be traced northwards into British America, Vancouver's Island, and the remote Queen Charlotte group, with no diminution in the thickness of the series of strata. The section at Skidegate Inlet in the latter islands is as follows:[2]—

Upper shales and sandstones. (Few fossils, the only form recognised being *Inoceramus problematicus*)	1,500 feet.
Conglomerates and sandstones (fragments of *Belemnites*) . .	2,000 „
Lower shales and sandstones with a workable seam of anthracite at the base (fossils abundant, including species of *Ammonites*, *Hamites*, *Belemnites*, *Trigonia*, *Inoceramus*, *Ostrea*, *Unio*, *Terebratula*, &c.)	5,000 „
Volcanic agglomerates, sandstones, and tuffs, with blocks sometimes four or five feet in diameter	3,500 „
Lower sandstones, some tufaceous, others fossiliferous . . .	1,000 „
.	13,000 „

Reference has already (p. 922) been made to the remarkable Cretaceous flora of Greenland. Three horizons of plant-bearing beds have there been met with: (*a*) the Kome beds—dark shales resting on the crystalline rocks, and containing what appears to be a Lower Cretaceous flora; (*b*) the Atane beds—greyish-black shales and sands (Upernivik, Noursoak, Disco, &c.), with Upper Cretaceous plants; (*c*) pale and red clays lying on the Atane beds. Marine fossils found in some of the Upper Cretaceous beds likewise serve to indicate their horizon.[3]

Australasia.—Representatives of the Cretaceous system occupy a vast area in Australia. In Queensland their lower member ("Rolling Downs Formation") is estimated to cover three-fourths of the whole of the colony. This group of strata is found in some districts to pass down conformably into the plant-bearing Jurassic rocks, and elsewhere to lie unconformably on ancient schists, slates, and granites. It has yielded numerous species of foraminifera, brachiopods, lamellibranchs (*Ostrea vesiculosa*, *Pecten*, *Aucella*, *Inoceramus*, *Pinna*, *Mytilus*, &c.), gasteropods, belemnites, ammonites of the genera *Amaltheus*, *Schlönbachia*, *Haploceras*, also *Hamites*, *Ancyloceras*, *Crioceras*, and *Nautilus*; likewise fishes of the genera *Lamna*, *Aspidorhynchus*, *Belonostomus*, and various ichthyosaurs and plesiosaurs. The Upper Cretaceous formations are represented by the "Desert Sandstone," which must have covered at least three-quarters of the colony. It lies on an upturned and denuded surface of the Lower Cretaceous formations and contains land-plants and a marine fauna (*Micraster*, *Rhynchonella*, *Ostrea*, *Trigonia*, *Belemnites*).[4]

In New Zealand the "Waipara" formation of Canterbury is believed to represent Upper Cretaceous and possibly some of the older Tertiary horizons. It consists of massive conglomerates (sometimes 6000 to 8000 feet thick), sandstones, shales, brown-coal seams, and ironstones. The plants include dicotyledonous leaves, cones, and branches of araucarians and leaves and twigs of *Dammara*. Among the shells no cephalopods nor any of the widespread hippurites have yet been found. With the remains of fishes (*Odontaspis*, *Lamna*, *Hybodus*) occur numerous saurian bones, which have been referred to species of *Plesiosaurus*, *Mauisaurus*, *Polycotylus*, &c.[1] According to the work of the Geological Survey Department of New Zealand, the Cretaceous system consists of a lower group (500 feet) of green and grey incoherent sandstones, in which beds of bituminous coal occur on the west coast (Lower Greensand), surmounted by a mass of strata (2000 to 5000 feet) which appears to connect the Cretaceous and Tertiary series. The upper part of the group (consisting of marls, greensand, limestone and chalk with flints) is thoroughly marine in origin, with *Ancyloceras*, *Belemnites*, *Rostellaria*, *Plesiosaurus*, *Leiodon*, &c. The lower portion, which is capped by a black grit with marine fossils, contains the most valuable coal-deposits of New Zealand. The plants include dicotyledonous and coniferous forms closely allied to those still living in the country.[2]

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[1] G. F. Becker, *Amer. Journ. Sci.* xxxi. (1886) p. 348.

[2] G. M. Dawson in *Report of Progress of Geol. Surv. Canada*, 1878-79; *Amer. Journ. Sci.* xxxviii. (1889) p. 120; *op. cit.* xxxix. (1890) p. 180. J. F. Whiteaves, *Mesozoic Fossils*, vol. i. parts i. iii. in publications of *Geol. Survey, Canada*. See also Mr. Dawson's *Report on Geology and Resources of the Region near the 49th Parallel, British North American Boundary Commission*, 1875; *Report on Canadian Pacific Railway*, Ottawa, 1880.

[3] Heer, 'Flora Fossilis Arctica,' vi. (1882).

[4] R. L. Jack and E. Etheridge, 'Geology of Queensland,' chaps. xxxi.-xxxiv.

PART IV. CAINOZOIC OR TERTIARY.

The close of the Mesozoic periods was marked in the west of Europe by great geographical changes, during which the floor of the Cretaceous sea was raised partly into land and partly into shallow marine and estuarine waters. These events must have occupied a vast period, so that, when sedimentation once more became continuous in the region, the organisms of Mesozoic time (save low forms of life) had, as a whole, disappeared and given place to others of a distinctly more modern type. In England, the interval between the Cretaceous and the next geological period represented there by sedimentary formations is marked by the abrupt line which separates the top of the Chalk from all later accumulations, and by the evidence that the Chalk seems to have been in some places extensively denuded before even the oldest of what are called the Tertiary formations were deposited upon its surface. There is evidently here a considerable gap in the geological record. We have no data for ascertaining what was the general march of events in the south of England between the eras chronicled respectively by the Upper Chalk and the overlying Thanet beds. So marked is this hiatus, that the belief was long prevalent that between the records of Mesozoic and Cainozoic time one of the great breaks in the geological history of the globe intervenes.

Here and there, however, in the continental part of the Anglo-Parisian basin, traces of some of the missing evidence are obtainable. Thus, the Maestricht shelly and polyzoan limestones, with a conglomeratic base, contain a mingling of true Cretaceous organisms with others which are characteristic of the older Tertiary formations. The common Upper Chalk crinoid, *Bourgueticrinus ellipticus*, occurs there in great numbers; also *Ostrea vesicularis*, *Baculites Faujasii*, *Belemnitella mucronata*, and the great reptile *Mosasaurus*; but associated with such Tertiary genera as *Voluta*, *Fasciolaria*, and others. At Faxoe, on the Danish island of Seeland, the uppermost member of the Cretaceous system (Danian) contains, in like manner, a blending of well-known Upper Chalk organisms with the Tertiary genera *Cypræa*, *Oliva*, and *Mitra*. In the neighbourhood of Paris also, and in scattered patches over the north of France, the Pisolitic Limestone, formerly classed as Tertiary, has been found to include so many distinctively Upper Cretaceous forms as to lead to its being relegated to the top of the Cretaceous series, from which, however, it is marked off by the decided unconformability already described. These fragmentary deposits are interesting, in so far as they help to show that, though in western Europe there is a tolerably abrupt separation between Cretaceous and Tertiary deposits, there was nevertheless no real break between the two periods. The one merged insensibly into the other; but the strata which would have served as the chronicles of the intervening ages have either never been deposited in the area in question, or have since been in great measure destroyed. In southern Europe, especially in the south-eastern Alps, and probably in other parts of the Mediterranean basin, no sharp line can be drawn between Cretaceous and Eocene rocks. These deposits merge into each other in such a way as to show that the geographical changes of the western region did not extend into the south and south-east. In North America, also, on the one side (pp. 928, 959), and in New Zealand on the other, there is a similar effacement of the hard and fast line which was once supposed to separate Mesozoic and Tertiary formations.

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[1] Etheridge, *Q. J. Geol. Soc.* xxviii. 183, 340; Owen, *Geol. Mag.* vii. 49; Hector, *Trans. New Zealand Inst.* vi. p. 333; Haast, 'Geology of Canterbury and Westland,' p. 291; Hutton and Ulrich, 'Geology of Otago,' p. 44.

[2] Hector, 'Handbook of New Zealand,' 1883, p. 29.

The name Tertiary, given in the early days of geology, before much was known regarding fossils and their history, has retained its hold on the literature of the science. It is often replaced by the terms "Cainozoic" (*recent life*), or "Neozoic" (*new life*), which express the great fact that it is in the series of strata comprised under these designations that most recent species and genera have their earliest representatives. Taking as the basis of classification the percentage of living species of mollusca found by Deshayes in the different groups of the Tertiary series, Lyell proposed a scheme of arrangement which has been generally adopted. The older Tertiary formations, in which the number of still living species of shells is very small, he named Eocene (*dawn of the recent*), including under that title those parts of the Tertiary series of the London and Paris basins wherein the proportion of existing species of shells was only 3½ per cent.[1] The middle Tertiary beds in the valleys of the Loire, Garonne, and Dordogne, containing 17 per cent of living species, were termed Miocene (*less recent*), that is, containing a minority of recent forms. The younger Tertiary formations of Italy were included under the designation Pliocene (*more recent*), because they contained a majority, or from 36 to 95 per cent, of living species. This newest series, however, was further subdivided into Older Pliocene (35 to 50 per cent of living species) and Newer Pliocene (90 to 95 per cent). A still later group of deposits was termed Pleistocene (*most recent*), where the shells all belonged to living species, but the mammals were partly extinct forms. This classification, though somewhat artificial, has, with various modifications and amplifications, been adopted for the Tertiary groups, not of Europe only, but of the whole globe. The original percentages, however, often depending on local accidents, have not been very strictly adhered to. The most important modification of the terminology in Europe has been the insertion of another stage or group termed Oligocene, proposed by Beyrich, to include strata that were formerly classed partly as Upper Eocene and partly as Lower Miocene.[1]

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[1] Some palæontologists, however, doubt whether any older Tertiary species, except of foraminifera or other lowly organisms, is still living.

Some writers, recognising a broad distinction between the older and the younger Tertiary deposits of Europe, have proposed a classification into two main groups: 1st, Eocene, Older Tertiary or Palæogene, including Eocene and Oligocene; and, 2nd, Younger Tertiary or Neogene, comprising Miocene and Pliocene. This subdivision has been advocated on the ground that, while the older deposits indicate a tropical climate, and contain only a very few living species of organisms, the younger groups point to a climate approaching more and more to that of the existing Mediterranean basin, while the majority of their fossils belong to living species.[2]

The Tertiary periods witnessed the development of the present distribution of land and sea and the upheaval of most of the great mountain-chains of the globe. Some of the most colossal disturbances of the terrestrial crust, of which any record remains, took place during these periods. Not only was the floor of the Cretaceous sea upraised into low lands, with lagoons, estuaries, and lakes, but throughout the heart of the Old World, from the Pyrenees to Japan, the bed of the early Tertiary or nummulitic sea was upheaved into a succession of giant mountains, some portions of that sea-floor now standing at a height of at least 16,500 feet above the sea.

During Tertiary time also there was an abundant manifestation of volcanic activity. After a long quiescence during the succession of Mesozoic periods, volcanoes broke forth with great vigour both in the Old and the New World. Vast floods of lava were poured out, and a copious variety of rocks was produced, ranging from highly basic to rhyolites, quartz-felsites, and granites.

The rocks deposited during these periods are distinguished from those of earlier times by increasingly local characters. The nummulitic limestone of the older Tertiary groups is indeed the only widespread massive formation which, in the uniformity of its lithological and palæontological characters, rivals the rocks of Mesozoic and Palæozoic time. As a rule, Tertiary deposits are loose and incoherent, and present such local variations, alike in their mineral composition and organic contents, as to show that they were mainly accumulated in detached basins of comparatively limited extent, and in seas so shallow as to be apt from time to time to be filled up or elevated, and to become in consequence brackish or even fresh.[1] These local characters are increasingly developed in proportion to the recentness of the deposits.

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[1] Boyd Dawkins has proposed to use the fossil mammalia as a basis of classification (*Q. J. Geol. Soc.* 1880, p. 379), but his scheme does not essentially differ from that in common use founded on molluscan percentages.

[2] Hörnes, *Jahrb. Geol. Reichsanst.* 1864, p. 510.

The climate during Tertiary time underwent in the northern hemisphere some remarkable changes. Judging from the terrestrial vegetation preserved in the strata, we may infer that in England the climate of the oldest Tertiary periods was of a temperate character,[2] but that it became during Eocene time tropical and subtropical, even in the centre of Europe and North America. It then gradually grew more temperate, but flowering plants and shrubs continued to live even far within the Arctic circle, where, then as now, unless the axis of the earth has meanwhile shifted, there must have been six sunless months every year. Growing still cooler, the climate passed eventually into a phase of extreme cold, when snow and ice extended from the Arctic regions far south into Europe and North America. Since that time, the cold has again diminished, until the present thermal distribution has been reached.

With such changes of geography and climate, the plant and animal life of Tertiary time, as might have been anticipated, is found to have been remarkably varied. Entering upon the Tertiary series of formations, we find ourselves upon the threshold of the modern type of life. The ages when lycopods, ferns, cycads, and yew-like conifers were the leading forms of vegetation, have passed away, and that of the dicotyledonous angiosperms —the hard-wood trees and evergreens of to-day—now succeeds them, but not by any sudden extinction and re-creation; for, as we have seen (p. 922), some of these trees had already made their appearance in Cretaceous times. The hippurites, inocerami, ammonites, belemnites, baculites, turrilites, scaphites, and other mollusks, which had played so large a part in the molluscan life of the later Secondary periods, now cease. The great reptiles, too, which, in such wonderful variety of type, were the dominant animals of the earth's surface, alike on land and sea, ever since the commencement of the Lias, now waned before the increase of the mammalia, which advanced in augmenting diversity of type until they reached a maximum in variety of form and in bulk just before the cold epoch referred to. When that refrigeration passed away and the climate became milder, the extraordinary development of mammalian life that preceded it is found to have disappeared also, being only feebly represented in the living fauna at the head of which man has taken his place.

Section 1. Eocene.

§ 1. General Characters.

ROCKS.—In Europe and Asia the most widely distributed deposit of this epoch is the nummulitic limestone, which extends from the Pyrenees through the Alps, Carpathians, Caucasus, Asia Minor, Northern Africa, Persia, Beloochistan, and the Suleiman Mountains, and is found in China and Japan. It attains a thickness of several thousand feet. In some places it is composed mainly of foraminifera (*Nummulites* and other genera); but it sometimes includes a tolerably abundant marine fauna. Here and there it has assumed a compact crystalline marble-like structure, and can then hardly be distinguished from a Mesozoic or even Palæozoic rock. Enormous masses of sandstone occur in the eastern Alps (Vienna sandstone, Flysch), referred partly to the same age, but seldom containing any fossils save fucoids (p. 955). The most familiar European type of Eocene deposits, however, is that of the Anglo-Parisian and Franco-Belgian area, where are found numerous thin local beds of usually soft and uncompacted clay, marl, sand, and sandstone, with hard and soft bands of limestone, containing alternations of marine, brackish, and fresh-water strata. This type of sedimentation evidently indicates more local and shallower basins of deposit than the wide Mediterranean sea, which stretched across the heart of the Old World in early Tertiary time.

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[1] The peculiar characters of the Tertiary rocks of the Western Territories of North America are, however, displayed over areas which in Europe would be regarded as enormous.

[2] J. S. Gardner in 'Geology of the Isle of Wight,' *Mem. Geol. Surv.* 1889, p. 106.

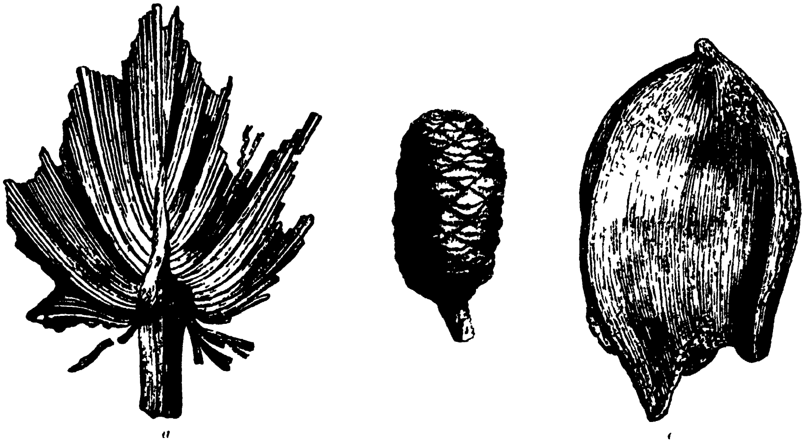

Fig 424 —Eocene Plants
a, Sabal oxyrhachis, Heer (reduced), *b*, Petrophiloides Richardsoni; *c*, Nipa Burtini, Brongn. sp. (½).

LIFE.—The flora of Eocene time has been abundantly preserved on certain horizons. In the English Eocene groups, a succession of several distinct floras has been observed, those of the London Clay and Bagshot beds being particularly rich. The plants from the London Clay indicate a warm climate.[1] They include species of *Callitris*, *Solenostrobus*, *Cupressinites*, *Sequoia*, *Salisburia*, *Agave*, *Smilax*, *Amomum*, *Nipa* (Fig. 424), *Magnolia*, *Nelumbium*, *Victoria*, *Hightea*, *Sapindus*, *Eucalyptus*, *Cotoneaster*, *Prunus*, *Amygdalus*, *Faboidea*, &c. Proteaceous plants like the living Australian *Petrophila* and *Isopogon* have been asserted to occur in the Lower Eocene vegetation, but their occurrence is not yet proved; the so-called *Petrophiloides* is now regarded as an alder (Fig. 424).[1] During Middle Eocene time in the umbrageous forests of evergreen trees—laurels, cypresses, and yews—there grew species of ferns (*Lygodium*, *Asplenium*, &c.), also of many of our familiar trees besides those just mentioned, such as chestnuts, beeches, elms, poplars, hornbeams, willows, figs, planes, and maples. The subtropical character of the climate was shown by clumps of Pandanus, with here and there a fan-palm (Fig. 424) or feather-palm, a tall aroid or a towering cactus.[2]

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[1] Ettingshausen, *Proc. Roy. Soc.* xxix. (1879) p. 388.

The Eocene fauna of western and central Europe presents similar evidence of tropical or subtropical conditions. Especially characteristic are foraminifera of the genus *Nummulites*, which occur in prodigious numbers in the nummulite limestone (Fig. 425), and also occupy different horizons in the English and French Eocene basins. The assemblage of mollusca is very large, most of the genera being still living, though many of them are confined to the warmer seas of the globe (Figs. 426, 427). Characteristic forms are *Belosepia*, *Nautilus*, *Cancellaria*, *Fusus*, *Pseudoliva*, *Oliva*, *Voluta*, *Conus*, *Mitra*, *Cerithium*, *Melania*, *Turritella*, *Rostellaria*, *Pleurotoma*, *Cypræa*, *Natica*, *Scala*, *Corbula*, *Cyrena*, *Cytherea* (*Meretrix*), *Chama*, *Lucina*.[3] Fish remains are not infrequent in some of the clays, chiefly as scattered teeth (Fig. 428) and otoliths. The living tropical siluroid genus *Arius* has been found in these deposits. Some of the more common genera are *Lamna*, *Odontaspis*, *Myliobates*, *Aetobates*, *Pristis*, *Phyllodus*. The Eocene reptiles present a singular contrast to those of Mesozoic time. They consist largely of tortoises and turtles, with crocodiles and sea-snakes. It is suggestive to find remains of siluroid fish, crocodiles, and chelonians, preserved in deposits of Eocene age, for the assemblage is like what may now

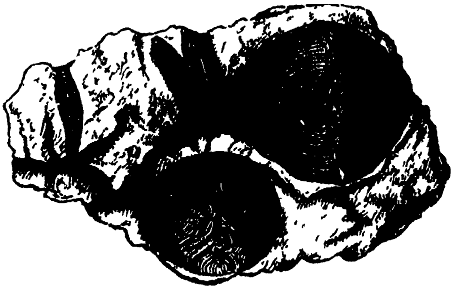

Fig. 425.—Nummulitic Limestone (¼).

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[1] J. S. Gardner, *op. cit.* p. 108.

[2] J. S. Gardner, "British Eocene Flora," *Palæontograph. Soc.* 1879; L. Crié, "Recherches sur la Végétation de l'Ouest de la France à l'Epoque Tertiaire," *Ann. Sciences Géol.* ix. (1877); Ettingshausen, *Proc. Roy. Soc.* xxx. (1880) p. 228; Comte de Saporta, 'Le Monde des Plantes,' 1879, p. 207.

[3] For a list of British Eocene and Oligocene mollusca consult the volume by R. B. Newton, one of the series of Catalogues issued by the British Museum.

be met with in tropical seas of the present time. An interesting series of remains of birds has been obtained from the English Eocene beds. These include *Argillornis longipennis* (perhaps representative of, but larger than, the modern albatross), *Dasornis*, and *Gastornis* (somewhat akin to the

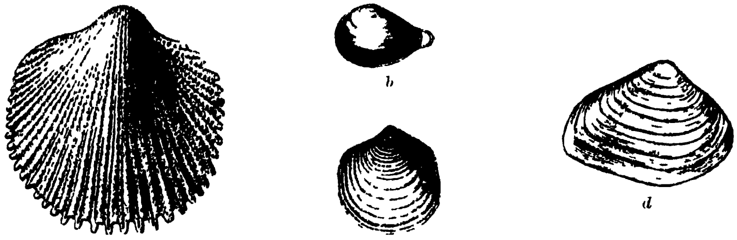

Fig 426.—Eocene Lamellibranchs
a, Cardium porulosum, Lam.; *b*, Corbula regulbiensis, Mor., *c*, Lucina squamula, Desh.; *d*, Cyrena cuneiformis, Sow. (⅔)

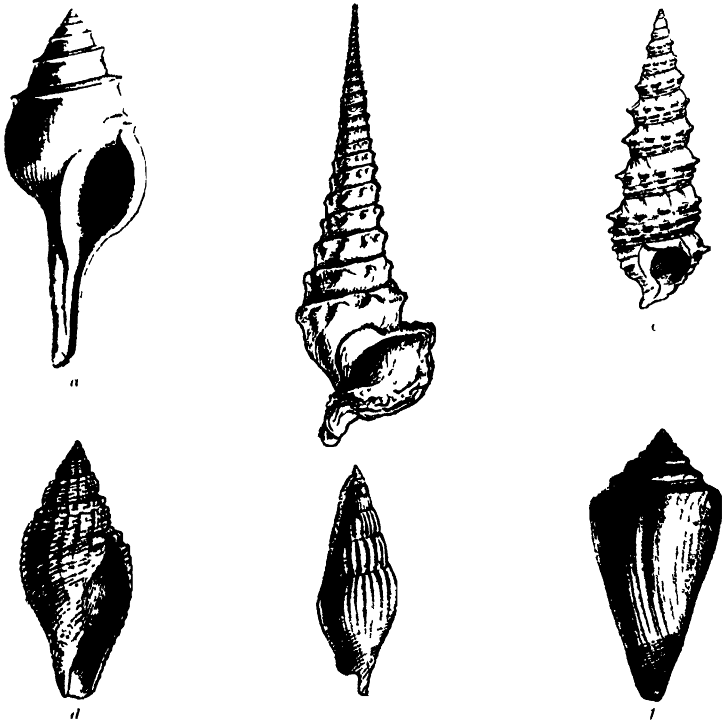

Fig. 427.—Eocene Gasteropods.
a, Fusus (Clavalithes) longævus, Brand. (½), *b*, Cerithium (Campanile) giganteum, Lam. (1/10), *c*. Melania inquinata, Defr. (½); *d*, Voluta (Volutilithes) elevata, Sow. (⅔); *e*, Rostellaria (Rimella) fissurella, Desh. (⅔); *f*, Conus deperditus, Brug. (½).

extinct *Dinornis* of New Zealand), *Halcyornis toliapicus*, *Lithornis vulturinus*, *Macrornis tanaupus*, *Odontopteryx toliapicus* (a bird with bony tooth-like processes to its large beak). From the upper Eocene beds of the Paris basin ten species of birds have been obtained, including forms allied to the buzzard, osprey, hawk, nuthatch, quail, pelican, ibis, flamingo, and African hornbill.[1] But the most notable feature in the palæontology of the period is the advent of some of the numerous mammalian forms for which Tertiary time was so distinguished. In the lower Eocene period appeared the primitive carnivores *Arctocyon* and *Palæonictis*, two animals with marsupial affinities, the former with bear-like teeth, the latter with teeth like those of the Tasmanian dasyure ; also the tapir-like *Coryphodon* ; the small hog-like *Hyracotherium*, with canine teeth like those of the peccary, and a form intermediate between that of the hog and the hyrax. Middle Eocene time was distinguished by the advent of a group of remarkable tapir-like animals (*Palæotherium*, *Palaplotherium*, *Lophiodon*,[2] *Pachynolophus*) ; true carnivores (*Pterodon* and *Proviverra*) ; insectivores (*Heterohyus*, *Microchœrus*) and the lemuroid *Cœnopithecus*, the earliest representative of the tribe of monkeys. With the upper Eocene period, besides the abundant older tapir-like forms, there came others (*Anchitherium*), which presented characters intermediate between those of the tapiroid Palæotheres and the true Equidæ. They were about the size of small ponies, had three toes on each foot, and are regarded as ancestors of the horse. Numerous hog-like animals (*Diplopus*, *Hyopotamus*) mingled with herds of ancestral hornless forms of deer and antelopes (*Dichobune*, *Dichodon*, *Amphitragulus*). Opossums abounded. Among the carnivores were animals resembling wolves (*Cynodon*), foxes (*Amphicyon*), and wolverines (*Tylodon*), but all possessing marsupial affinities. There appear to have been also representatives of our hedgehogs, squirrels, and bats.[3]

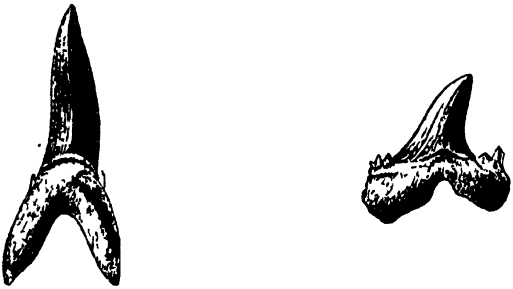

Fig 428.—Eocene Fishes.

a, Lamna elegans, tooth of, Ag. (4) , *b*, Odontaspis (Otodus) obliquus, tooth of Ag. (5)

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[1] Owen, *Q. J. Geol. Soc.* 1856, 1873, 1878, 1880 ; Boyd Dawkins, 'Early Man in Britain,' p. 33 ; Milne Edwards, 'Oiseaux Fossiles,' ii. 543.

[2] H. Filhol, *Mem. Géol. Soc. France* (3) v. No. 1 (1888).

[3] Gaudry, 'Les Enchainements du Monde Animal,' p. 4 ; Boyd Dawkins, 'Early Man in Britain,' chap. ii.

It is from the thick Eocene lacustrine formations of the western Territories of the United States that the most important additions to our knowledge of the animals of early Tertiary time have been made, thanks to the admirable and untiring labours, first of Leidy, and subsequently of Marsh at Newhaven, and Cope at Philadelphia. The Laramie group, in particular, has yielded an extraordinarily abundant and varied fauna, comprising ophidians (*Coniophis*), true lacertilians (*Chamops*, *Iguanavus*), and gigantic forms of deinosaurs. These last-named animals are of peculiar interest, inasmuch as they show that just before the final extinction of the sub-class to which they belong they had developed into many highly specialized types (*Ornithomimus*, *Claosaurus*).[1] The herbivorous ungulata appear to have formed a chief element in this western fauna. They included some of the oldest known ancestors of the horse, with four-toed feet, and even in one form (*Eohippus*) with rudiments of a fifth toe; also various hog-like animals (*Eohyus*, *Parahyus*). Some of the most peculiar forms were those of the type termed Tillodont by Marsh, presenting a remarkable union of the characters of ungulates, rodents, and carnivores, and especially striking from their pair of long incisor teeth (*Tillotherium*, *Anchippodus*, *Calamodon*). This author, from another assemblage of skulls and bones of animals about as large as a fox, has proposed to establish a separate order of mammals, that of the Mesodactyla, which in his opinion stands in somewhat the same relation to the typical Ungulates that the Tillodonts do to Rodents.[2] Still more extraordinary were the Deinocerata, ranked as a distinct sub-order, possessing, according to Marsh, the size of elephants, with the habits of rhinoceroses, but bearing a pair of long horn-like prominences on the snout, another pair on the

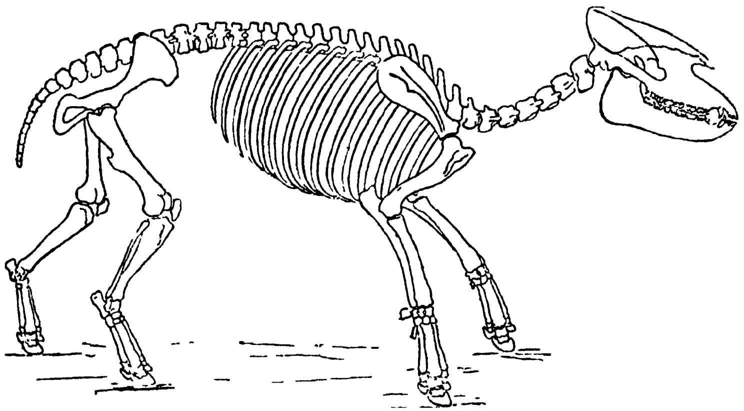

Fig. 429.—Palæotherium magnum, Cuv. ($\frac{1}{20}$)

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[1] O. Marsh, *Amer. Journ. Sci.* xliii. (1892) p. 449.

[2] Marsh, *op. cit.* (1892) p. 445. Compare H. F. Osborn, *Journ. Acad. Philadelph.* ix. (1888).

forehead, and a single one on each cheek (*Uintatherium*, Fig. 430,[1] with the forms described under the names *Deinoceras*, *Tinoceras*, Fig. 431, *Octotomus*, *Eobasileus*, *Loxolophodon*). With these animals there coexisted large and small carnivores and some lemuroid monkeys.

§ 2. Local Development.

Britain.[2] — Entirely confined to the south-eastern part of England,[3] the British Eocene strata occupy two synclinal depressions in the Chalk, which, owing to denudation, have become detached into the two well-defined basins of London and Hampshire. They have been arranged as in the subjoined table :—

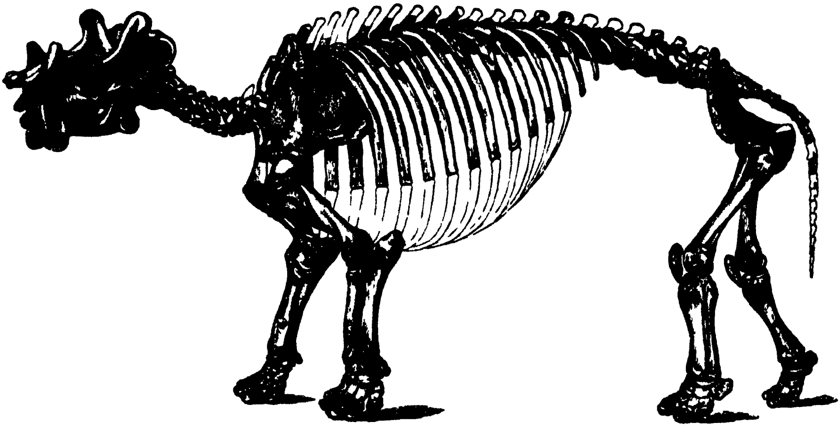

Fig. 430.— Deinoceras (Uintatherium) mirabile, Marsh ($\frac{1}{30}$).

	Hampshire.	*London.*
Upper.	Headon Hill or Barton Sands. Barton Clay.	Upper Bagshot Sands.
Middle.	Bracklesham beds, and leaf beds of Bournemouth and Alum Bay.	Middle Bagshot beds, part of Lower Bagshot Sands.

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[1] This restoration was kindly supplied by Prof. Marsh, whose Monograph on the Deinocerata the student should consult. *Mon. U.S. Geol. Surv.* vol. x. (1886).

[2] See Conybeare and Phillips, 'Geology of England and Wales'; Prestwich, *Q. J. Geol. Soc.* vols. iii. vi. viii. x. xi. xiii.; Edward Forbes, 'Tertiary Fluvio-marine Formation of the Isle of Wight,' *Mem. Geol. Surv.* 1856; H. W. Bristow, C. Reid, and A. Strahan, 'Geology of the Isle of Wight,' *Mem. Geol. Surv.* 2nd edition, 1889; Whitaker, 'Geology of London,' *Mem. Geol. Surv.* 1889; Phillips, 'Geology of Oxford and the Thames Valley,' 1871.

[3] Mr. J. S. Gardner, however, has classed as Eocene the plant-bearing beds of Bovey, Antrim, &c., described at p. 988 under the Oligocene subdivision.

	Hampshire.	*London.*
Lower.	London Clay (Bognor beds). Woolwich and Reading beds.	Part of Lower Bagshot Sands. London Clay. Oldhaven beds. Woolwich and Reading beds. Thanet Sand.

LOWER EOCENE.—The Thanet Sand[1] at the base of the London basin consists of pale yellow and greenish sands, sometimes clayey, and containing at their bottom a thin, but remarkably constant, layer of green-coated flints resting directly on the Chalk. According to Mr. Whitaker, it is doubtful if proof of actual erosion of the Chalk can anywhere be seen under the Tertiary deposits in England, and he states that the Thanet Sand everywhere lies upon an even surface of Chalk with no visible unconformability.[2] Professor Phillips, on the other hand, describes the Chalk at Reading as having been "literally ground down to a plane or undulated surface, as it is this day on some parts of the Yorkshire coast," and having likewise been abundantly bored by lithodomous shells.[3] The Thanet Sand appears to have been formed only in the London basin; at least it has not been recognised at the base of the Eocene series in Hampshire. It has yielded numerous organic remains in East Kent, but is almost unfossiliferous farther west. Its fossils comprise about 70 known species (all marine except a few fragments of terrestrial vegetation). Among them are several foraminifera, numerous lamellibranchs (*Astarte tenera*, *Cyprina scutellaria* (*planata*), *Ostrea bellovacina*, *Cucullæa decussata* (*crassatina*), *Pholadomya* (*martesia?*) *cuneata*, *P. Koninckii*, *Corbula regulbiensis*, &c.), a few species of gasteropods (*Natica infundibulum* (*subdepressa*), *Aporrhais Sowerbii*, &c.), a nautilus, and the teeth, scales, and bones of fishes (*Odontaspis*, *Pisodus*).

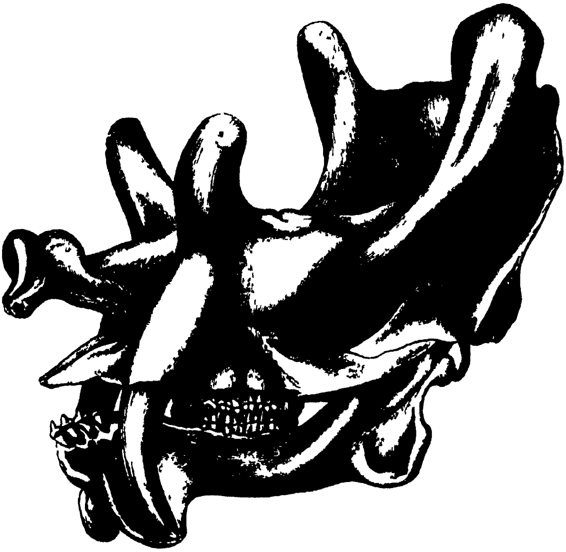

Fig. 431. Skull of Tinoceras (Uintatherium) ingens, Marsh (about $\frac{1}{11}$).

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[1] Prestwich, *Q. J. Geol. Soc.* viii. (1852) p. 237.

[2] 'Geology of London,' p. 107.

[3] 'Geology of Oxford,' p. 442.

The Woolwich and Reading Beds,[1] or "Plastic Clay" of the older geologists, consist of lenticular sheets of plastic clay, loam, sand, and pebble-beds, so variable in character and thickness over the Tertiary districts that their homotaxial relations would not at first be suspected. One type (Reading) presenting unfossiliferous lenticular, mottled, bright-coloured clays, with sands, sometimes gravels, and even sandstones and conglomerates, occurs throughout the Hampshire basin and in the northern and western part of the London basin. A second type (Woolwich), found in West Kent, Surrey, and Sussex, from Newhaven to Portslade, consists of light-coloured sands and grey clays, crowded with estuarine shells. A third type, seen in East Kent, is composed only of sands containing marine fossils. These differences in lithological and palæontological characters serve to indicate the geographical features of the south-east of England at the time of deposit, showing in particular that the sea of the Thanet beds had gradually shallowed, and that an estuary now partly extended over its site. The organic remains as yet obtained from this group amount to more than 100 species. They include a few plants of terrestrial growth, such as *Ficus Forbesi*, *Grevillea Heeri*, *Laurus Hookeri*, *Aralia*, *Lygodium*, *Liriodendron*, *Palmetto*, and *Platanus*—a flora which, containing some apparently persistent types, has a temperate facies.[2] The lamellibranchs are partly estuarine or fresh-water, partly marine; characteristic species being *Cyrena cuneiformis*, *C. cordata*, and *C. tellinella*. *Ostrea bellovacina* forms a thick oyster-bed at the base of the series, besides occurring throughout the group. *Ostrea tenera* is likewise abundant. The gasteropods include a similar mixture of marine with fluviatile species (*Potamides* (*Cerithium*) *funatus*, *Melania inquinata*, *Melanopsis buccinoides*, *Neritina globulus*, *Natica infundibulum*, *Pisania* (*Fusus*) *lata*, *Viviparus* (*Paludina*) *lentus*, *Planorbis lævigatus*, *Pitharella Rickmanni*, &c.) The fish are chiefly sharks (*Odontaspis*). Bones of turtles, scutes of crocodiles, and remains of gigantic birds (*Gastornis*) have been found. The highest organisms are bones of mammalia, including the *Coryphodon*.

The Blackheath or Oldhaven Beds,[3] at the base of the London Clay, consist in W. Kent almost wholly of rolled flint-pebbles in a sandy base, which, as Mr. Whitaker suggests, may have accumulated as a bank at some little distance from shore. Though of trifling thickness (20-40 feet), they have yielded upwards of 150 species of fossils. Traces of *Ficus*, *Cinnamomum*, and *Coniferæ* have been obtained from them, indicating perhaps a more subtropical character than the flora of the beds below, but without the Australian and American types which appear in so marked a manner in the later Eocene floras.[4] The organisms, however, are chiefly marine and partly estuarine shells, the gasteropods being particularly abundant (*Calyptræa trochiformis*, *Potamides* (*Cerithium*) *funatus*, *Melania inquinata*, *Natica infundibulum*, *Cardium plumstediense*, *Pectunculus terebratularis*, &c.)

The London Clay[5] is a deposit of stiff brown and bluish-grey clay, with layers of septarian nodules of argillaceous limestone. Its bottom beds, commonly consisting of green and yellow sands, and rounded flint-pebbles, sometimes bound by a calcareous cement into hard tabular masses, form in the London basin a well-marked horizon. The London Clay is typically developed in that basin, attaining its maximum thickness (500 feet) in the south of Essex. Its representative in the Hampshire basin, known as the "Bognor Beds," and exposed at Bognor on the Sussex coast and at Portsmouth, consists of clays, sands, and calcareous sandstones, thus differing somewhat, both lithologically and palæontologically, from the typical development in the London basin. The London Clay has yielded a long and varied suite of organic remains, that point to its having been laid down in the sea beyond the mouth of a large estuary, into which abundant relics of the vegetation, and even sometimes of the fauna, of the adjacent land were swept. According to Prof. T. Rupert Jones, the depth of the sea, as indicated by the foraminifera of the deposit, may have been about 600 feet. Professor Prestwich has pointed out that there are traces of the existence of palæontological zones in the clay, the lowest zone indicating, in the east of the area of deposit, a maximum depth of water, while a progressive shallowing is shown by three higher zones, the uppermost of which contains the greater part of the terrestrial vegetation, and also most of the fish and reptilian remains. The fossils are mainly marine mollusca, which, taken in connection with the flora, indicate that the climate was somewhat tropical in character. The plants include the fruits, seeds, or leaves of the following, among other genera, the fossils having been mostly obtained from the Isle of Sheppey: *Sequoia, Pinus, Callitris, Salisburia; Musa, Nipa, Sabal, Chamærops; Quercus, Liquidambar, Laurus, Nyssa, Diospyros, Symplocos, Magnolia, Victoria, Hightea, Sapindus, Cupania, Eugenia, Eucalyptus, Amygdalus.*[1] Diatoms are plentifully diffused through the London Clay, and numerous foraminifera have been found by washing it. Crustacea abound (*Xanthopsis, Hoploparia*). Of the lamellibranchs some of the most usual genera are *Avicula, Cardium, Corbula, Leda, Modiola, Nucula*, and *Pinna*. Gasteropods are the prevalent mollusks, the common genera being *Pleurotoma* (45 species), *Fusus* (15 species), *Cypræa, Murex, Natica, Cassis* (*Cassidaria*), *Pyrula*, and *Voluta*. The cephalopods are represented by 6 or more species of *Nautilus*, by *Belosepia sepioidea*, and *Beloptera Levesquei*. Nearly 100 species of fishes occur in this formation, the rays (*Myliobates*, 14 species) and sharks (*Odontaspis, Lamna*, &c.) being specially numerous. A sword-fish (*Tetrapterus priscus*), and a saw-fish (*Pristis*) have likewise been met with. The reptiles were numerous, and markedly unlike, as a whole, to those of Secondary times. Among them are numerous turtles and tortoises (*Chelone*, 10 species, *Trionyx*, 1 species, *Platemys*, 6 species), two species of crocodile, and a sea-snake (*Palæophis toliapicus*), estimated to have equalled in size a living *Boa constrictor*. Remains of birds have also been met with (*Lithornis vulturinus, Halcyornis toliapicus, Dasornis londinensis, Odontopteryx toliapicus, Argillornis longipennis*). The mammals included forms resembling the tapirs (*Hyracotherium, Coryphodon*, &c.), an opossum (*Didelphys*), and a bat. The carcases of these animals must have been borne seawards by the great river which transported so much of the vegetation of the neighbouring land.

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[1] Prestwich, *Q. J. Geol. Soc.* x. p. 75; Whitaker, 'Geology of London,' p. 122.

[2] J. S. Gardner, "British Eocene Flora," *Palæontog. Soc.* p. 29.

[3] Whitaker, *Q. J. Geol. Soc.* xxii. (1866), p. 412; 'Geology of London,' p. 214.

[4] J. S. Gardner, *op. cit.* pp. 2, 10.

[5] Prestwich, *Q. J. Geol. Soc.* vi. p. 255; x. p. 435; Whitaker, 'Geology of London,' p. 238.

MIDDLE EOCENE.—In the London basin this division consists chiefly of sands, which are comprised in the two sub-stages of the lower and middle "Bagshot Beds." The lower of these, consisting of yellow, siliceous, unfossiliferous sands, with irregular light clayey beds, attains a thickness of about 100 to 150 feet. The second sub-stage, or "Middle Bagshot Beds," is made up of sands and clays, sometimes 50 or 60 feet thick, containing few organic remains, among which are bones of turtles and sharks, with a few mollusks (*Cardita acuticosta, C. elegans, C. planicosta, C. imbricata, Corbula gallica, C. Lamarckii, Ostrea flabellula*).

In the Hampshire basin, the Middle Eocene beds attain a much greater development, being not less than 660 feet thick at the west end of the Isle of Wight, where they consist of variously-coloured unfossiliferous sands and clays, with minor beds of ironstone and plant-bearing clays, pointing to an alternation of marine and estuarine conditions of deposit.[2] On the mainland at Studland, Poole, and Bournemouth, the same beds appear. The important series of clays, marls, sands, and lignites, upwards of 100 feet thick, known as the Bracklesham beds from their occurrence at Bracklesham, on the coast of Sussex, has yielded a large series of marine organisms. Among these are the fishes *Pristis, Odontaspis, Lamna, Myliobates*, also *Palæophis*, and the mollusks *Belosepia sepioidea, B. Owenii, Cypræa inflata, C. tuberculosa, Marginella eburnea, M. ovulata, Voluta crenulata, V. spinosa, V. angusta, V. Branderi, V. cythara, V. muricina, Mitra labratula, Conus deperditus, C. Lamarckii, Pleurotoma dentata, P. textiliosa, Pteronotus* (*Murex*) *asper, Clavalithes* (*Fusus*) *longævus, Turritella imbricataria, Ostrea dorsata, O. flabellula, Pseud-amusium* (*Pecten*) *corneus, P. squamula, Lima expansa, Spondylus rarispina, Avicula media, Pinna margaritacea, Modiola* (*Lithodomus?*) *Deshayesi, Arca biangula* (*Branderi*), *A. interrupta, A. planicosta, Limopsis granulata, Nucula minor, Nuculana* (*Leda*) *galeottiana, Cardita acuticosta, C. elegans, C. imbricata, C. planicosta, Crassatella grignonensis, Chama calcarata, C. gigas, Nummulites lævigata,* (*N. scabra*) *Alveolina fusiformis.*[1] The Bracklesham beds reappear to a small extent, as greenish clayey sands, in the London basin, where they form part of the Middle Bagshot beds.

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[1] Ettingshausen and Gardner, "British Eocene Flora," *Palæontograph. Soc.* p. 12; Ettingshausen, *Proc. Roy. Soc.* xxix. (1879).

[2] 'Geology of the Isle of Wight' in *Mem. Geol. Surv.* p. 109.

One of the most characteristic features of the English Middle Eocene division is the abundant terrestrial flora which has been disinterred especially from the plant-beds of Alum Bay and Bournemouth. It is remarkable that this vegetation is apt to occur in patches or "pockets" which may mark the sites of pools into which it was blown by wind or transported by streams, so that varied though it be, it probably affords no adequate picture of the variety of the flora from which it was derived. From Alum Bay, in the Isle of Wight, according to Ettingshausen's census, no fewer than 116 genera and 274 species belonging to 63 families have been obtained.[2] A feature of special interest in this flora is to be found in the fact that it is the most tropical in general aspect which has yet been studied in the northern hemisphere. This character is particularly indicated by the numbers of species of fig, and by the Artocarpeæ, Cinchonaceæ, Sapotaceæ, Ebenaceæ, Buttneriaceæ, Bombaceæ, Sapindaceæ, Malpighiaceæ, &c. The most conspicuous and typical forms are *Ficus Bowerbankii, Aralia primigenia, Dryandra acutiloba, D. Bunburyi, Cassia Ungeri*, and the fruits of *Cæsalpina*. Many of the dicotyledons belong to species elsewhere found in what have been considered to be Miocene deposits. More than fifty species of the Alum Bay flora are found also in those of Sotzka and Häring (p. 979), while a lesser number occur in those of Sézanne (p. 976) and the Lignitic series of Western America.[3] The Bournemouth beds are believed to be rather higher in the series than those of Alum Bay, and lie immediately below the Bracklesham beds. None of the prevailing types of plants are found in them that occur at Alum Bay, but this may no doubt be due to local accidents of deposition. The Bournemouth flora is likewise an abundant one, and suggests a comparison of its climate and forests with those of the Malay archipelago and tropical America.[4] The celebrated lignitiferous deposit of Bovey Tracey in Devonshire has been referred by Mr. Gardner to this horizon.[5] Crocodiles still haunted the waters, for their bones are mingled with those of sea-snakes and turtles, and with tapiroid and other older Tertiary types of terrestrial creatures. The occurrence of the foraminiferal genus *Nummulites* is noteworthy. Though not common in England, it abounds, as already stated, in the Eocene deposits of central and eastern Europe.

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[1] See Dixon's 'Geology of Sussex;' Edwards and S. Wood, "Monograph of Eocene Mollusca," *Palæontograph. Soc.*

[2] Mr. Gardner suspects that in this estimate species from other localities have been included with those from Alum Bay, 'Geology of the Isle of Wight' in *Mem. Geol. Surv.* p. 105.

[3] Ettingshausen, *Proc. Roy. Soc.* 1880, p. 228. See J. S. Gardner, *Geol. Mag.* 1877, p. 129; *Nature*, vol. xxi. (1879) 181, the Monograph on Eocene Flora already cited, and 'Geology of the Isle of Wight' in *Mem. Geol. Surv.* p. 104.

[4] J. S. Gardner, *Q. J. Geol. Soc.* xxxv. (1879) p. 209; xxxviii. (1882) p. 1; *Proc. Geol. Assoc.* v. p. 51; viii. p. 305; *Geol. Mag.* 1882, p. 470.

[5] *Quart. Journ. Geol. Soc.* xxxv. p. 227; xxxviii. p. 3. For an account of this deposit and its flora, see W[illegible]lly and O. Heer, *Phil. Trans.* 1862.

UPPER EOCENE.—The highest division of the Eocene strata of England, according to the classification here followed, includes the uppermost part of the Hampshire series, which has long been known as the "Barton Clay," with, perhaps, the Upper Bagshot Sand of the London basin. The Barton Clay does not occur in that basin, but forms an important feature in Hampshire, where, on the cliffs of Hordwell, Barton, and in the Isle of Wight, it attains a thickness of 300 feet. It consists of grey, greenish, and brown clays, with bands of sand, and has long been well known for the abundance and excellent preservation of its fossils, chiefly mollusks, of which more than 500 species have been collected, but including also fishes (*Lamna*, *Myliobates*, *Arius*) and a crocodile (*Diplocynodon*). The following list includes some of the more important species for purposes of comparison with equivalent foreign deposits: *Voluta luctatrix*, *V. ambigua*, *V. athleta*, *Conorbis* (*Conus*) *scabriculus*, *C. dormitor*, *Pleurotoma rostrata* (and numerous other species), *Clavalithes* (*Fusus*) *longævus*, *Leistoma pyrus*, *Ostrea gigantea*, *O. flabellula*, *Vulsella deperdita*, *Pecten reconditus*, *Lima compta*, *L. soror*, *Avicula media*, *Modiola seminuda*, *M. sulcata*, *M. tenuistriata*, *Arca appendiculata*, *Axinæa* (*Pectunculus*) *deleta*, *Cardita Davidsoni*, *C. sulcata*, *Crassatella sulcata*, *Chama squamosa*, *Nummulites elegans*, *N. variolaria*.

In the London basin the position of the so-called "Upper Bagshot Sands" has been the subject of some discussion, there being no marked separation between them and the group known as "Middle Bagshot." They consist of sands with ferruginous concretions which have yielded *Turritella imbricataria*, *Ostrea flabellula*, and other shells found in the Barton Clay.

Above the Barton Clay and forming the highest member of the Eocene series comes a mass of unfossiliferous or sparingly fossiliferous sand, from 140 to 200 feet in thickness, so purely siliceous as to be valuable for glass-making. These deposits in the Isle of Wight are immediately covered by the base of the Oligocene series. They have been called "Upper Bagshot," but as they probably occupy a higher horizon than the true Upper Bagshot Sand of the London basin, the local term Headon Hill Sand or Barton Sand is more convenient for them.[1]

It is probably from the Bagshot sands that the great majority of the so-called "Grey Wethers" or "Druid stones" of the south of England have been derived, which have already (p. 355) been referred to.

Northern France and Belgium.[2]—The anticline of the Weald which separates the basins of London and Hampshire is prolonged into the Continent, where it divides the Tertiary areas of Belgium from those of Northern France. There is so much general similarity among the older Tertiary deposits of the whole area traversed by this fold as to indicate a probable original relation as parts of one great tract of sedimentation. Local differences, such as the replacement of fresh-water beds in one region by marine beds in another, together with occasional gaps in the record, show us some of the geographical conditions and oscillations during the time of deposition. The following table gives the general grouping and correlation of the Eocene formations in this region:—

Upper.	Marine gypsum of Paris basin. Middle sands (Sables Moyens).	Wemmelian sands of Belgium.

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[1] C. Reid, 'Geology of the Isle of Wight,' *Mem. Geol. Surv.* p. 122.

[2] For a comparison of the Lower Eocene groups of Paris, Belgium and England, see Hébert, *Bull. Soc. Géol. France* (3), ii. p. 27. Prestwich (*Brit. Assoc.* 1882, p. 538) regards the Sables de Bracheux as representing only the lower part of the Woolwich beds.

Middle.	Caillasses or Upper Calcaire Grossier (fresh-water).	Lackenian sands.
	Middle Calcaire Grossier (marine).	Bruxellian sands and sandstones.
	Lower Calcaire Grossier (fresh-water).	
Lower.	Sands of Cuise and Soissons.	Paniselian sands.
	Plastic clays and lignite.	Ypresian sands and clays.
	Limestones of Rilly and Sézanne.	
	Sands of Bracheux and Meudon Marl.	Landenian sands.

LOWER EOCENE.—In the Paris basin, the Sables de Bracheux form an excellent horizon, which corresponds to the Thanet Sand of England and Dumont's "Système Landenien" in Belgium. Below this horizon, there occurs in the Franco-Belgian region a lower series of deposits than is found in England.[1] In the Paris basin, these strata present variable and local characters. They include the Marnes de Meudon, remarkable for containing 20 per cent of carbonate of strontia; and the limestones of Rilly and Sézanne—a form of travertine from which fresh-water shells and a rich assemblage of plants have been obtained (*Chara*, *Asplenium*, *Alsophylla*, *Juglandites*, *Sassafras*, *Hedera*, &c.)[2] To the north of Paris, the Marnes de Meudon disappear, and their place is taken by the Sables de Bracheux—greenish glauconitic sands with a basement-band of green-coated flints resting generally directly on the Chalk. This sandy member of the series, traceable as a definite platform through the Anglo-French and Belgian area, contains among its characteristic fossils *Pholadomya cuneata*, *P. Koninckii*, *Cyprina Morrisii*, *Cucullæa crassatina*, *Pecten breviauritus*, *Psammobia Edwardsii*, *Ostrea bellovacina*, *Corbula regulbiensis*, *Turritella bellovacina*, *Natica deshayesiana*, *Voluta depressa*. Higher in the series comes the "Argile plastique" of the Paris basin, with the associated lignites of the Soissonnais. The molluscan fauna of these strata resembles that of the Woolwich and Reading beds. But a break seems to occur in the series at this point; for in the Paris basin no representative of the London Clay is found. The lignites of the Soissonnais are covered by sands (Sables de Cuise or du Soissonnais) containing, among other abundant marine organisms, *Nummulites planulata*, *Turritella edita*, *T. hybrida*, *Crassatella propinqua*, *Lucina squamula*; they are regarded as the equivalent of the lower part of the English Bagshot Sand, and form the highest member of the Lower Eocene stages of the Paris basin.

In the Belgian area, some differences are presented in the succession of sediments. The strata of that district have been grouped by Dumont into a series of "systèmes." The most ancient Tertiary deposit of the west of Europe appears to be the limestone of Mons (Système Montien). This rock lies in a denuded hollow of the Chalk, and has been found by boring to be more than 300 feet thick. It consists of friable and compact limestone, charged with a remarkable series of organic remains. Upwards of 400 species of fossils have been obtained from it, including marine, fresh-water, and terrestrial shells. Among them are about 200 species of gasteropods, about 125 lamellibranchs, and fifty polyzoa, besides numerous foraminifers (*Quinqueloculina*), and calcareous algæ (*Dactylopora*, *Acicularia*, &c.) Two conspicuous features in this deposit are the extraordinary proportion of its new and peculiar species, and the resemblance of its fauna, especially its numerous Cerithiums and Turritellas, to that of the Middle Eocene beds of Belgium and the Paris basin rather than to that of the Lower Eocene. The Mons limestone has thus been cited as an illustration of Barrande's doctrine of colonies.[3]

Above this deposit comes the "Système Heersien," so named from its development at Heers, in Limbourg. With a total depth of about 100 feet, it consists of (1) a lower division of sandy beds, with *Cyprina planata*, *C. Morrisii*, *Modiola elegans*, and other marine shells, some of which occur in the Thanet Sand of England and the Sables de Bracheux; and (2) an upper division of marls, containing, besides some of the marine shells found in the lower division, numerous remains of a terrestrial vegetation (*Osmunda eocenica, Chamæcyparis belgica, Poacites latissimus*, and species of *Quercus, Salix, Cinnamomum, Laurus, Viburnum, Hedera, Aralia*, &c.)[1]

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[1] Hébert, *Ann. Sciences Géol.* iv. (1873) Art. iv. p. 14.

[2] Saporta, *Mém. Soc. Géol. France* (2) viii.; 'Le Monde des Plantes,' p. 212 *et seq.*

[3] Briart and Cornet, *Mém. Couronn. Acad. Roy. Belg.* xxxvi. (1870); xxxvii. (1873); xliii. (1880). Mourlon, 'Géol. Belg.' 1880, p. 192. Hébert (*Ann. Sciences Géol.* iv. 1873, p. 15) has noticed an affinity to the uppermost Cretaceous fauna of Paris.

The "Système Landenien," corresponding to the Thanet and Woolwich and Reading beds of England and the Sables de Bracheux, Argile plastique, and Lignites du Soissonnais of France, is divisible into two stages: 1st, Lower marine gravels, conglomerates, sandstones, marls, &c., with badly preserved fossils, among which are *Turritella bellovacina, Cucullæa decussata* (*crassatina*), *Cardium Edwardsi, Cyprina planata, Corbula regulbiensis, Pholadomya Koninckii*; 2nd, Upper fluvio-marine sands, sandstones, marls, and lignites containing *Melania inquinata, Melanopsis buccinoides, Cerithium funatum, Ostrea bellovacina, Cyrena cuneiformis*, with leaves and stems of terrestrial plants.

The "Système Yprésien" consists of a great series of clays and sands answering generally to the London Clay, but not represented in France. It is divided into two stages: 1st, Lower stiff grey or brown clay (Argile de Flanders ou d'Ypres), sometimes becoming sandy, and probably an eastward extension of the London Clay. The break between this deposit and the top of the Landenian beds below is regarded as filled up by the Oldhaven beds of the London basin. The only recorded fossils are foraminifera agreeing with those of the London Clay. 2nd, Upper sands with occasional lenticular intercalations of thin greyish-green clays, with abundant fossils, the most frequent of which are *Nummulites planulata* (forming aggregated masses), *Turritella edita, T. hybrida, Vermetus bognorensis, Pecten corneus, Pectunculus decussatus, Lucina squamula, Ditrupa plana*. Out of 72 species of mollusks, 45 are found also in the Sables de Cuise and 20 in the London Clay.[2]

The "Système Paniselien," so named from Mont Panisel near Mons, consists chiefly of sandy deposits not markedly fossiliferous, but containing among other forms *Rostellaria fissurella, Voluta elevata, Turritella Dixoni, Cytherea ambigua, Lucina squamula*. Out of 129 species of mollusca found in this deposit, 91 appear in the Sables de Cuise, and only 36 pass up into the Calcaire Grossier. Hence the Paniselian beds are placed at the top of the Lower Eocene stages of Belgium.

MIDDLE EOCENE. - This division in the Paris basin is formed by the characteristic, prodigiously fossiliferous Calcaire Grossier, which is subdivided as under:[3]—

Caillasses or Upper (Fresh-water) Calcaire Grossier.	Upper subgroup with *Cardium obliquum* and *Cerithium denticulatum*.	4.	Limestone with *Cardium obliquum* and *Cerithium Blainvilli*.	
		3.	Limestone with *Cerithium denticulatum* and *C. costatum*.	
		2.	Siliceous limestone with undetermined forms of *Potamides*.	
		1.	Coral limestone (*Stylocœnia*).	
	Middle subgroup with *Lucina saxorum* and *Miliola*.	4.	Siliceous limestone with parting of laminated marl.	
		3.	Limestone in small thin boards with *Corbula* (Rochette).	
		2.	Limestone with *Miliola* and *Lucina saxorum* (Roche).	
		1.	Siliceous limestone with indeterminate fossils (Bancs francs).	
	Lower subgroup with *Cerithium lapidum* and *Miliola*.	4.	Limestone (dolomitic) with *Miliola* (Cliquart).	
		3.	Green marl . . . . . Siliceous limestone in two beds Green marl	Blanc vert.
		2.	Miliola limestone (dolomitic) (Saint Nom).	
		1.	Siliceous limestone with *Potamides*.	

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[1] De Saporta and Marion, *Mém. Cour. Acad. Roy. Belg.* xli. (1878).

[2] Mourlon, 'Géol. Belg.' p. 211.

[3] Dollfus, *Bull. Soc. Géol. France*, 3^{e} sér. vi. (1878) p. 269. Compare Michelet, *op. cit.* 2^{e} sér. xii. p. 1336.

Middle Calcaire Grossier.

5. Limestone with *Lucina concentrica*, *Arca barbatula*, *Cardium aviculare*, *Miliola*, &c.
4. Limestone with *Orbitolites*, *Fusus bulbiformis*, *Volvaria bulloides*, *Cardium granulosum*, *Arca quadrilatera*, several species of large *Flustra* or *Membranipora*.
3. Limestone with *Fabularia* and terrestrial vegetation (*Orbitolites complanata*, *Chama calcarata*, *Cardita imbricata*, &c.)
2. Mass of *Miliola* limestone (*Turritella imbricataria*, *Chama calcarata*, *Lucina mutabilis*, &c.)
1. Limestone with *Miliola* and *Terebratula* (*T. bisinuata*).

Lower Calcaire Grossier.

5. Glauconitic calcaire grossier with *Cerithium giganteum*.
4. Glauconitic calcareous sand with *Lenita patellaris*.
3. Sandy glauconitic calcaire grossier with *Cardium porulosum*.
2. Sandy glauconitic calcaire grossier, with *Nummulites lævigata*, *N. scabra*, *Ostrea multicostata*, *O. flabellula*, *Ditrupa plana*.
1. Glauconitic sand, sometimes calcareous and indurated, with pebbles of green quartz, shark's teeth, and rolled fragments of coral.

In **Belgium** the Middle Eocene presents a different aspect from that of Paris, approximating rather to the English Type. It consists of (1) a lower set of sandy beds grouped under the name of "Bruxellien," rich in fossils, which, however, are usually badly preserved. Among the forms are remains of terrestrial vegetation (*Nipa Burtini*), also *Paracyathus crassus*, *Maretia grignonensis*, *Pyripora contesta*, *Ostrea cymbula*, *Cardita decussata*, *Chama calcarata*, *Cardium porulosum*, *Cerithium unisulcatum*, *Natica labellata*, *Voluta lineola*, *Ancillaria buccinoides*, *Clavalithes* (*Fusus*) *longævus*, numerous remains of fishes, especially of the genera *Myliobates*, *Odontaspis*, *Lamna*, *Galeocerdo*, and various reptiles, including species of *Trionyx* and *Chelone*, with *Emys Camperi*, *Gavialis Dixoni*, and *Palæophis typhæus*; (2) a group of sands and fossiliferous calcareous sandstones ("Lackenien"), made up of *Ditrupa strangulata* and *Nummulites* (*N. lævigata*, *N. scabra*, *N. Héberti*, *N. variolaria*), and abounding in *Anomia sublævigata*.

UPPER EOCENE.—In the **Paris basin** this subdivision consists of the following stages:[1]—

Gyps Marin.

- Gypsum with nodules of silica (menilite), and containing marine fossils (*Cerithium tricarinatum*, *C. pleurotomoides*, *Turritella incerta*).
- Yellow marls with *Lucina inornata*.
- Gypsum, saccharoid and crystallized, with brown marls.
- Yellow, brown, and greenish marls, with *Pholadomya ludensis*, *Crassatella Desmaresti*, &c.

Sables Moyens.

- Green sands of Monceaux (*Cerithium Cordieri*, *C. tricarinatum*, *Natica parisiensis*).
- Limestones of Saint Ouen—a marly fresh-water rock 20 to 26 feet thick, composed of two zones, the lower full of *Bythinia*, and the upper abounding in *Limnæa*.
- Sands of Mortefontaine (*Avicula Defrancei*).
- Sands and sandstones of Beauchamp (*Cerithium mutabile*, *C. tuberculosum*, *C. Bouei*, *Melania hordacea*, *M. lactea*, *Cyrena deperdita*, *Planorbis nitidulus*, *Corbula gallica*, &c.)
- Sands, &c., with *Nummulites variolaria*, *Ostrea dorsata*, *Cyrena deperdita*, corals, *Lamna elegans*, *Odontaspis* (*Otodus*) *obliquus*, &c.

Northwards in the **Belgian** area, near Brussels, the highest Eocene strata consist of sands and calcareous sandstones ("Wemmelien"), separated from the similar Lackenian beds below by a gravel full of *Nummulites variolaria*. Other common fossils are *Turbinolia sulcata*, *Corbula pisum*, *Cardita sulcata*, *Turritella brevis*, *Clavalithes* (*Fusus*) *longævus*.

Receding from the Paris basin, the Eocene deposits assume entirely different characters as they are traced into the west, centre, and south of France. According to

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[1] See Dollfus, *op. cit.*

Vasseur's detailed researches, a long irregular arm of the sea penetrated Brittany in Eocene times from where the Loire now enters the Atlantic, while the north-western part of Vendée was likewise submerged. In these waters a series of limestones and sands was deposited, which from their fossil contents appear to be the equivalents of the Calcaire Grossier. They pass up into lacustrine and brackish-water beds like the corresponding groups at Paris.[1] In the south of France, the Eocene rocks chiefly present the nummulitic facies to be immediately referred to, and in some places attain a great development, as near Biarritz, where they are more than 3000 feet thick.

Southern Europe.—The contrast between the facies of the Cretaceous system in north-western and in southern Europe is repeated with even greater distinctness in the Eocene series of deposits. From the Pyrenees eastwards, through the Alps and Apennines into Greece and the southern side of the Mediterranean basin, through the Carpathian Mountains and the Balkan into Asia Minor, and thence through Persia and the heart of Asia to the shores of China and Japan, a series of massive limestones has been traced, which, from the abundance of their characteristic foraminifera, have been called the Nummulitic Limestone. Unlike the thin, soft, modern-looking, undisturbed beds of the Anglo-Parisian area, these limestones attain a depth of sometimes several thousand feet of hard, compact, sometimes crystalline rock, passing even into marble; and they have been folded and fractured on such a colossal scale that their strata have been heaved up into lofty mountain crests sometimes 10,000, and in the Himalaya range more than 16,000, feet above the sea. With the limestones is associated the sandy series known as Nummulite Sandstone. The massive unfossiliferous Vienna sandstone and Flysch, already referred to as probably in part Cretaceous, are no doubt also partly referable to Eocene time.[2] One of the most remarkable features of these Alpine Eocene deposits is the occurrence in them of coarse conglomerates and gigantic erratics of various crystalline rocks. As far east as the neighbourhood of Vienna, and westward at Bolgen near Sonthofen in Bavaria, near Habkeren and in other places, blocks of granite, granitite, and gneiss occur singly or in groups in the Eocene strata. These travelled masses appear to have most petrographical resemblance, not to any Alpine rocks now visible, but to rocks in southern Bohemia. Their presence may possibly indicate the existence of glaciers in the middle of Europe during some part of the Eocene age.[3] Another interesting Eocene deposit of the Alpine region is the coal-bearing group of Haring, in the Northern Tyrol, where a seam of coal occurs which, with its partings, attains a thickness of 32 feet.

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[1] G. Vasseur, *Ann. Sci. Géol.* xiii. (1881). Hébert, *Bull. Soc. Géol. France* (3) x. (1882) p. 364.

[2] The history of the Flysch has given rise to some discussion. Th. Fuchs, for instance, regarded it as having probably been derived from eruptive discharges such as those of mud volcanoes (*Sitz. Akad. Wien*, lxxv. 1877, p. 340; *Verh. Geol. Reichsanst.* 1878, p. 135). This view was opposed by K. M. Paul, who looked on the Flysch as a normal sedimentary formation (*Jahrb. Geol. Reichsanst.* 1877, p. 431; *Verh. Geol. Reichsanst.* 1878, p. 179). By some geologists the rocks have been regarded as a deep-sea deposit, by others as an accumulation in shallow water (Renevier, *Arch. Sci. Phys. Nat. Geneva*, (3) xii. 1884, p. 310). See also Mantovani, *Neues Jahrb.* 1877; Schardt and Favre, 'Description Géol. des Préalpes du Canton de Vaud,' &c. 1887. Kauffmann, 'Description de la partie nord-ouest de la feuille xii. de la Carte Géol. Suisse,' 1886. F. Sacco, *Bull. Soc. Belge de Géol.* iii. (1889) p. 153. C. Mayer-Eymar, 'Versuch einer Classification der tertiar Gebilde Europas,' *Verh. Schweitz. Naturf. Ges.* 1857.

[3] That a glacial period occurred at the close of the Cretaceous period, again at the end of the Eocene and in the Miocene (erratics of Superga, near Turin) has been regarded by some geologists as probable (A. Vézian, *Rev. Sci.* xi. (1877) p. 171; Schardt, 'Etudes Géologiques sur le pays d'Enhaut Vaudois,' *Bull. Soc. Vaud*, 1884).

The Nummulitic series has been divided into stages in different regions of its distribution, and attempts have been made by means of the included fossils to parallel these stages in a general way with the subdivisions in the Anglo-Parisian basin. But the conditions of deposition were so different that such correlations must be regarded as only wide approximations to the truth. In the Northern Alps (Bavaria, &c.) Gümbel arranges the Eocene series as under:[1]—

Flysch or Vienna sandstone (Upper Eocene), including younger Nummulitic beds and Häring beds.

Lower Nummulitic group. Kressenberg beds—greenish sandy strata abounding in fossils, which on the whole point to a correspondence with the Calcaire Grossier.

Burberg beds—greensand with small Nummulites and *Exogyra Brongniarti*, answering possibly to the upper part of the lower Eocene beds of the Anglo-Parisian area.

In the southern and south-eastern Alps the Eocene rocks attain a much larger development. The following subdivisions in descending order have been recognised:[2]

Upper Eocene.	Macigno or Tassello, having the usual character of the Vienna sandstone. No fossils but fucoids.
	Fossiliferous calcareous marls and shales, and thick conglomerates.
Nummulite-Limestone.	Chief Nummulite limestone, containing the most abundant and varied development of nummulites, and attaining the thickest mass and widest geographical range.
	Borelis (Alveolina) limestone, containing numerous large foraminifera of the genus *Borelis*.
	Lower Nummulite limestone, with small nummulites, and in many places banks of corals.
Liburnian Stage.	Upper Foraminiferal limestone, containing also intercalations of fresh-water beds (*Chara*).
	Cosina beds, with a peculiar fresh-water fauna (*Stromatopsis*, *Melania*, *Chara*, &c.)
	Lower Foraminiferal limestone, with numerous marine mollusca (*Anomia*, *Cerithium*, &c.), and occasional beds of fresh-water limestone (*Chara*, *Melania*, &c.)

In the central part of the northern Apennines Professor Sacco regards as Eocene a mass of strata 5500 feet thick, which he subdivides as follows[3]:—

Bartonian. 100 metres.	Grey marls with sandy calcareous layers; numerous fossils (*Zoophycus*, *Lithothamnium*, *Nummulites Tchihatcheffi*, *N. striata*, *Orbitoides radians*, *Operculina*, corals, bryozoa, crinoids, &c.)
Parisian. 1500 metres.	A thick series of marly and shaly limestones (Flysch), alternating with sandstones (*Helminthoidea labyrinthica*, *Chondrites* and other fucoids). Roofing slates.
	Shales and sandstones (Macigno).
	Sandy greyish and brownish marls with calcareous sandy beds (*Lithothamnium*, *Nummulites biarritzensis*, *N. Lamarcki*, *N. lucasana*, *Assilina exponens*, *A. granulosa*, *Orbitoides*, *Operculina*, *Alveolina*, corals, echini, crinoids, fish-teeth, &c.)
Suessonian. 100 metres.	Shales and grey and brown marls, sandstones and limestones.

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[1] 'Geognostische Beschreib. Bayerisch. Alpen,' 1861, p. 593 *et seq.*

[2] Von Hauer, 'Geologie,' p. 569. For an exhaustive account of the stratigraphy and palæontology of the Liburnian stage, see G. Stache's great monograph, 'Die Liburnische Stufe,' *Abhandl. k. k. Geol. Reichsanst.* xiii. 1889. On the classification of the older Tertiary formations of Austria, consult Tietze, *Zeitsch. Deutsch. Geol. Ges.* xxxvi. (1884) p. 68; xxxviii. (1886) p. 26; T. Fuchs, *op. cit.* xxxvii. (1885) p. 131.

[3] Prof. Sacco has contributed many papers on this subject. See, for example, *Bull. Soc. Géol. France* (3) xvii. (1889) p. 212.

To the Upper Eocene series of this region has been assigned a great series of serpentines, gabbros, diabases, soda-potash granites, and other eruptive rocks, with tuffs and conglomerates, marking copious submarine volcanic activity.[1]

India, &c.—As above stated, the massive Nummulitic limestone extends through the heart of the Old World, and enters largely into the structure of the more important mountain chains. In India a tolerably copious development of Eocene rocks has been observed, but it is not quite certain where their upper limit should be drawn to place them on a parallel with the corresponding groups in Europe. The following subdivisions in descending order are observed in Sind :[2]—

Nari group. Sandstones without marine fossils, and probably of fresh-water origin, 4000 to 6000 feet, representing, perhaps, Upper Eocene and Oligocene or Lower Miocene beds of Europe.

Kasauli and Dagshai groups of sub-Himalayas.

Kirthar group. A marine limestone formation in general, but passing locally into sandstones and shales. The upper limestones contain *Nummulites garansensis*, *N. sublævigata*.

Nummulitic limestone of Sind, Punjab, Assam, Burmah, &c. Subathú of sub-Himalayas, Indus or Shingo beds of Western Tibet.

Ranikot beds—sandstones, shales, clays with gypsum and lignite, 1500 to 2000 feet ; abundant marine fauna, including *Nummulites spira*, *N. irregularis*, *N. Leymeriei*.

Lower Nummulitic group of Salt Range.

North America.—Tertiary formations of marine origin extend in a strip of low land along the Atlantic border of the United States and Mexico, from the coast of New Jersey southward into Florida and round the margin of the Gulf of Mexico, whence they run up the valley of the Mississippi to beyond the mouth of the Ohio. On the western seaboard they also occur in the coast ranges of California and Oregon, where they sometimes have a thickness of 3000 or 4000 feet, and reach a height of 3000 feet above the sea. Over the Rocky Mountain region Tertiary strata cover an extensive area, but are chiefly of fresh-water origin.

In the States bordering the Atlantic and Gulf of Mexico the oldest Tertiary deposits are referred to the Eocene series, and in some places (New Jersey) appear to follow conformably on the Cretaceous rocks. They have been subdivided into four groups, which in the state of Mississippi are well developed, with the following characters :[3]—

4. Jackson beds ("White Limestone" of Alabama), white and blue marls underlain by lignitic clay and lignite (80 feet) with *Zeuglodon macrospondylus*, *Cardita planicosta*, *Cardium Nicolleti*, *Leda multilineata*, *Corbula bicarinata*, *Rostellaria velata*, *Voluta dumosa*, *Mitra dumosa*, *Conus tortilis*, *Cypræa fenestralis*, &c.
3. Claiborne beds, white and blue marls, and sandy beds with numerous shells which indicate a horizon equivalent to that of part of the Calcaire Grossier of the Paris basin.
2. Buhrstone (Siliceous Claiborne), sandstones and siliceous impure limestones with Claiborne fossils (400 feet and upwards).
1. Lignitic sands and clays, with marine fossils, and with interstratified lignites and plant-remains (*Quercus*, *Populus*, *Ficus*, *Laurus*, *Persea*, *Cornus*, *Olea*, *Rhamnus*, *Magnolia*, &c.)

Over the Rocky Mountain region and the vast plateaux lying to the east of that range the older Tertiary formations consist mainly of lacustrine strata of great thickness, the extraordinary richness of which in vertebrate and particularly mammalian remains, already referred to (p. 969), has given them a high importance in geological and palæontological history. The following subdivisions in descending order were established some years ago :—

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[1] C. de Stefani, *Boll. Soc. Geol. Ital.* viii. fasc. 2 (1889) ; a copious list of previous writers on the subject will be found in this paper.

[2] Medlicott and Blanford, 'Geology of India,' chap. xix.

[3] A. Heilprin, 'Contributions to the Tertiary Geology and Palæontology of the United States,' 1884 ; *Proc. Acad. Philadelph.* 1887.

4. Uinta group (400 feet) or "Diplacodon beds."
3. Bridger group (5000 feet) or "Deinoceras beds."
2. Green River group (2000 feet).
1. Wahsatch (Vermilion Creek) group (5000 feet).

More recent researches in Colorado and elsewhere have somewhat modified this grouping. In the Denver region the so-called "Laramie" series (p. 958) has been found to consist of three divisions : (1) a lower member, 700 to 800 feet thick, conformable with the Cretaceous Fox Hills group, containing productive coal-seams and a flora and fauna characteristic of the Laramie group as usually understood ; (2) a middle member, called the Arapahoe group, resting on the first unconformably, with a conglomerate at its base, containing pebbles of the underlying formation and other older rocks ; (3) an upper member, the Denver group, 1400 feet thick, unconformable to the middle division, and largely composed of the débris of andesitic lavas. The strong unconformability between the Laramie beds (No. 1) and the Arapahoe group (No. 2) is believed to mark a considerable interval of time between the highest Cretaceous and oldest Tertiary deposits of this region.[1] In southern Colorado the Eocene strata have been described as 7000 feet thick, resting unconformably on the Laramie series. The lowest member (Poison Cañon), 3500 feet thick, and the next division (Cuchara), 300 feet thick, are classed as Lower Eocene ; the upper (Huerfano), 3300 feet thick, is believed to be equivalent to the Bridger group.[2]

Australasia.—Though vast areas in this region are covered with strata which sometimes attain a depth of several hundred feet, containing both terrestrial and marine deposits, and which are referable to various parts of Cainozoic time, no satisfactory correlation of the beds with European equivalents has yet been made, if, indeed, such a correlation is at all probable or possible. All that can be safely affirmed is that a succession among these beds can be traced with an increasing proportion of recent species in the younger parts of the series. Throughout the whole of eastern Australia, including most of New South Wales and Queensland, no marine Tertiary fossils have been discovered. In the south-west of New South Wales and in Victoria, previous to the eruption of basalt-sheets and tuffs, an extensive series of conglomerates, siliceous sandstones, clays, ironstones, and lignites was deposited in valleys and probably lake-basins. On the Dividing Range these strata rise to 4000 feet above the sea. At Bacchus Marsh in Victoria and elsewhere they have yielded leaves of *Laurus*, *Cinnamomum*, &c., some of which closely resemble species found at Oeningen. The general aspect of this flora is rather that of tropical than of extra-tropical Australia, and this indication of a warmer temperature than at present is corroborated by the occurrence of coral-reefs in Tasmania referred to the Miocene period. Above these plant-bearing beds which have been regarded as Lower Miocene or Upper Eocene, marine deposits supposed to be Middle and Upper Miocene occur on the flanks of the Dividing Range of New South Wales up to heights of 800 feet. In South Australia and Victoria extensive marine accumulations of clay, sand, and limestone, often underlying widespread basalt-plateaux, have yielded numerous foraminifera, especially at Mount Gambier and Murray Flats in South Australia ; 40 species of corals, which are only slightly related to the living species of the surrounding seas, but include three

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[1] Whitman Cross, *Amer. Journ. Sci.* xxxvii. (1889) p. 261 ; xliv. (1892) p. 19 ; *Proc. Colorado Sci. Soc.* Oct. 1892.

[2] R. C. Hills, *Proc. Colorado Sci. Soc.* iii. (1888) p. 148, (1889) p. 217 (1891).

European Tertiary species;[1] many echinoderms and polyzoa, and a large molluscan fauna, in which the genera *Waldheimia, Cucullæa, Pectunculus, Trigonia, Cypræa, Fusus, Haliotis, Murex, Mitra, Trivia, Turritella, Voluta,* &c., occur. The vertebrate organisms consist of fishes (including the world-wide genera *Carcharodon, Lamna, Odontaspis, Oxyrhina*), a few marsupials (*Bettongia, Nototherium, Phascolomys, Sarcophilus*), with some marine mammalia (*Squalodon, Arctocephalus*). In South Australia the older Tertiary deposits have been divided by Professor Tate into four groups, which in ascending order are: (*a*) Inferior marine beds, chalk-rocks, clays, and limestones; (*b*) Lower Murravian sandstones with *Zeuglodon, Lovenia, Magasella, Megalaster;* (*c*) Middle Murravian limestones and sandstones, with an abundant and varied marine fauna (*Charcarodon, Lamna, Odontaspis, Nassa, Ancillaria, Cassis, Voluta, Marginella, Mangelia, Cerithium, Conus, Cancellaria, Natica, Pecten, Lima, Spondylus, Nucula, Limopsis, Chama, Chione, Rhynchonella, Terebratulina, Waldheimia, Terebratula, Eupatagus, Deltocyathus,* &c.; (*d*) Upper Murravian oyster-beds and sandstones (*Trigonia, Pectunculus, Tellina, Mactra, Clypeaster,* &c.)

In Tasmania an important series of older Tertiary deposits has also been found. At the top, leaf-beds, lignites, and beds with marine fossils occur, associated with extensive sheets of felspar-basalts and tuffs. The tuffs have yielded *Hypsiprimnus* and *Phascolomys.* Next comes a great series of sandstones, clays, and lignites, varying from 400 to 1000 feet in thickness, and sometimes, as in the Launceston basin, covering an area of at least 600 square miles. This series encloses a rich flora, including species of oak, elm, beech, laurel, cinnamon, and araucaria, with fruits of proteaceous, sapindaceous, and coniferous trees. The fresh-water and terrestrial character of the deposits is further confirmed by the occurrence in them of *Unio, Helix, Vitrina, Bulimus,* &c. The third group in descending order is of marine origin, and is well seen at Table Cape. It consists of shelly limestones, calcareous sandstones, coral-rag and pebbly bands, and is replete with fossils, only from 1 to 3 per cent of the shells belonging to existing species. Characteristic forms are *Voluta anticingulata, Cassis sufflatus, Cypræa Archeri, Ancillaria mucronata, Panopæa Agnewi, Waldheimia garibaldiana, Lovenia Forbesi, Cellepora gambierensis.*[2]

In New Zealand rocks believed to be referable to the upper part of the Eocene series are mainly composed of a shelly calcareous sandstone with corals and polyzoa, which in its lower part passes occasionally into an imperfect nummulitic limestone (Nummulitic beds, Hutchison's Quarry beds, Mount Brown beds). Volcanic action was greatly developed during the deposit of these strata in both islands. Hence interbedded lavas and tuffs are frequent, and in the North Island the calcareous deposits are often wholly replaced by wide-spread trachyte-flows and volcanic breccias.[3]

Section ii. Oligocene.

§ 1. General Characters.

The term "Oligocene" was proposed in 1854 and again in 1858 by Professor Beyrich[4] to include a group of strata distinct from the Eocene formations of France and Belgium, and which Lyell had classed as "Older Miocene." They consist partly of terrestrial, partly of fresh-water and brackish, and partly of marine strata, indicating considerable oscillations of level in the European area. They consequently present none of the massive deep-water characters so conspicuous in some of the Eocene subdivisions. Among other geographical changes of which they preserve the chronicles is the evidence of the gradual conversion of portions of the sea-floor over the heart of Europe into wide lake-basins in which thick lacustrine deposits were accumulated. Some of these lakes did not attain their fullest development until the Miocene period.

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[1] Duncan, *Q. J. Geol. Soc.* 1870, p. 313. See also the papers of R. Tate, F. M'Coy, J. E. Tennison Woods, R. Etheridge jun., F. von Muller, Ettingshausen, and R. M. Johnston.

[2] Mr. R. M. Johnston, Registrar-General at Hobart, Tasmania, has published a useful memoir entitled, "Observations with respect to the Nature and Classification of the Tertiary Rocks of Australasia" (1888), with references to the principal sources of information on the subject of Tasmanian Tertiary geology.

[3] Hector's 'Handbook of New Zealand,' p. 28.

[4] *Monatsbericht. Akad. Berlin,* 1854, pp. 640-666; 1858, p. 51.

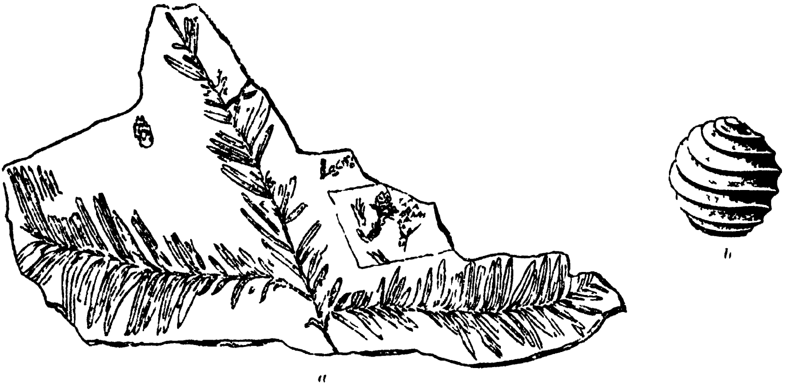

Fig. 432. Oligocene Plants.
a, Sequoia Langsdorfii, Brongn. (½) (from Heer's 'Flor. Tert. Helvetiae,' i. pl. 21),
b, Chara Lyellii, Forbes ($\frac{10}{1}$).

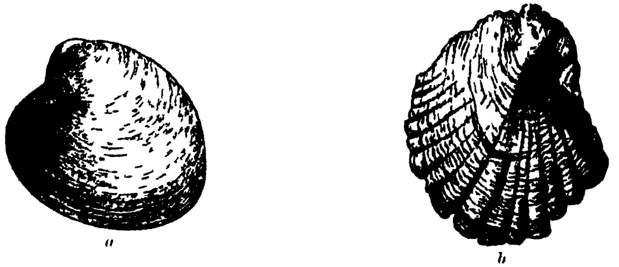

Fig. 433.—Oligocene Lamellibranchs.
a, Meretrix (Cytherea) incrassata, Sow. (⅔); *b*, Ostrea cyathula, Lam. (½)

The Oligocene **flora**, according to Heer, is composed mainly of an evergreen vegetation, and has characters linking it with the living tropical floras of India and Australia and with the subtropical flora of America. It includes some ferns, fan-palms, and feather-palms (*Sabal, Phœnicites*), a number of conifers (*Sequoia*, Fig. 432, &c.), cinnamon-trees, evergreen oaks, custard-apples, gum-trees, spindle-trees, oaks, figs, laurels, willows, vines, and proteaceous shrubs (*Dryandra, Dryandroides*).

Among the mollusca (Figs. 433, 434) some of the more important genera are *Ostrea*, *Pecten*, *Nucula*, *Cardium*, *Meretrix* (*Cytherea*), *Cyrena*, *Cancellaria*, *Murex*, *Fusus*, *Typhis*, *Cassis*, *Pleurotoma*, *Conus*, *Voluta*, *Cerithium*, *Melania*, *Planorbis*.[1] Numerous remains of birds have been found in the lacustrine beds of the Department of the Allier, no fewer than 66 species having been described, which comprise parroquets, trogons, flamingoes, ibises, pelicans, marabouts, cranes, secretary-birds, eagles, grouse, and numerous gallinaceous birds—a fauna reminding us of that of the lakes in Southern Africa.[2] The mammalia increase in variety of forms. According to Gaudry the following chronological sequence of appearances and disappearances during the Oligocene period have been noted:[3]—

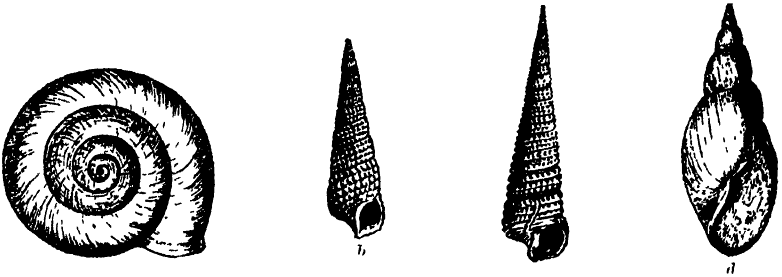

Fig. 434. Oligocene Gasteropods.
a, Planorbis euomphalus, Sow. ($\frac{2}{3}$); *b*, Terebralia (Cerithium) plicata, Lam. ($\frac{1}{3}$); *c*, Potamides cinctus, Sow. ($\frac{2}{3}$); *d*, Limnæa longiscata, Brongn. ($\frac{2}{3}$).

Upper.—St. Gérand-le-Puy (Allier), Calcaire de Beauce in part, Sables de Fontainebleaux, Hamstead beds.	Appearance of the genera *Rhinoceros* (?), *Tapir*, *Palæochærus*, shrew, *Plesiosorex*, *Mysarachne*, mole, musk-rat, *Lutrictis*, *Palæonycteris*, *Tetracus*. Disappearance of *Palæotherium*. Reign of *Hyopotamus* and *Anthracotherium*.
Middle.—Calcaire de Brie, &c.	Appearance of the genera *Cadurcotherium*, *Hyrachius*, *Entelodon*, *Anthracotherium*, *Dacrytherium*, *Chalicotherium*, *Tragulohyus*, *Lophiomeryx*, *Hyæmoschus* (?), *Gelocus*, *Dremotherium*, *Thereutherium*, dog (?), civet, marten, *Plesictis*, *Plesiogale*, *Ælurogale*, *Rhinolophus*, *Necrolemur*.
Lower. — Lacustrine gypsum of Paris, beds of Vaucluse, St. Hippolyte, Caton, Souvignargues, Bembridge beds.	Appearance of the genera opossum, *Chœropotamus*, *Tapirulus*, *Anoplotherium* (Fig. 435), *Eurytherium*, *Cainotherium*, *Anchilophus*, *Acotherulum*, *Cebochœrus*, *Xiphodon*, *Amphimeryx*, *Plesiarctomys*, dormouse (?), *Trechomys*, *Galethylax* (?), *Hyænodon*, *Adapis*. Reign of pachyderms. The carnivora have still partly marsupial characters.

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[1] For a list of British Oligocene mollusca, see Mr. R. B. Newton's volume cited on p. 966.

[2] A. Milne Edwards, 'Oiseaux Fossiles de la France,' 1867-71; Boyd Dawkins, 'Early Man in Britain,' p. 54.

[3] 'Les Enchaînements du Monde Animal,' 1878, p. 4.

formations of France and Belgium, and which Lyell had classed as "Older Miocene." They consist partly of terrestrial, partly of fresh-water and brackish, and partly of marine strata, indicating considerable oscillations of level in the European area. They consequently present none of the massive deep-water characters so conspicuous in some of the Eocene subdivisions. Among other geographical changes of which they preserve the chronicles is the evidence of the gradual conversion of portions of the sea-floor over the heart of Europe into wide lake-basins in which thick lacustrine deposits were accumulated. Some of these lakes did not attain their fullest development until the Miocene period.

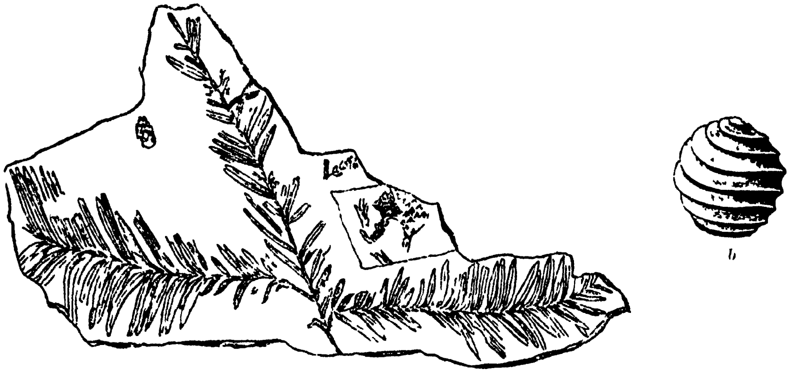

Fig 432 Oligocene Plants
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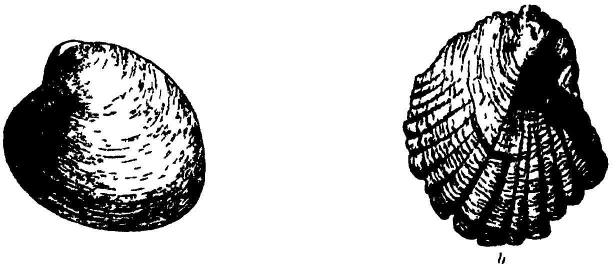

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The Oligocene flora, according to Heer, is composed mainly of an evergreen vegetation, and has characters linking it with the living tropical floras of India and Australia and with the subtropical flora of America. It includes some ferns, fan-palms, and feather-palms (*Sabal*, *Phœnicites*), a number of conifers (*Sequoia*, Fig. 432, &c.), cinnamon-trees, evergreen oaks, custard-apples, gum-trees, spindle-trees, oaks, figs, laurels, willows, vines, and proteaceous shrubs (*Dryandra*, *Dryandroides*).

Among the mollusca (Figs. 433, 434) some of the more important genera are *Ostrea*, *Pecten*, *Nucula*, *Cardium*, *Meretrix* (*Cytherea*), *Cyrena*, *Cancellaria*, *Murex*, *Fusus*, *Typhis*, *Cassis*, *Pleurotoma*, *Conus*, *Voluta*, *Cerithium*, *Melania*, *Planorbis*.[1] Numerous remains of birds have been found in the lacustrine beds of the Department of the Allier, no fewer than 66 species having been described, which comprise parroquets, trogons, flamingoes, ibises, pelicans, marabouts, cranes, secretary-birds, eagles, grouse, and numerous gallinaceous birds—a fauna reminding us of that of the lakes in Southern Africa.[2] The mammalia increase in variety of forms. According to Gaudry the following chronological sequence of appearances and disappearances during the Oligocene period have been noted:[3]—

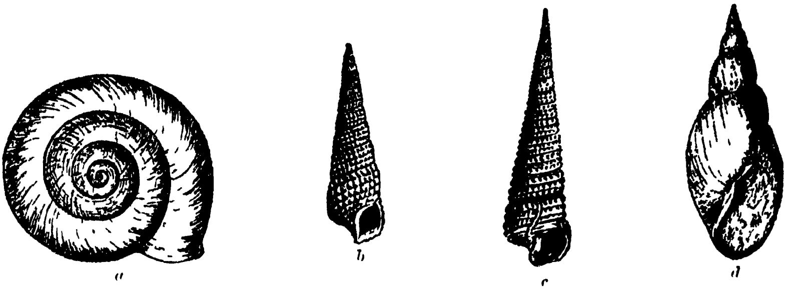

Fig. 434. Oligocene Gasteropods.

a, Planorbis euomphalus, Sow. (⅔); *b*, Terebralia (Cerithium) plicata, Lam. (⅔); *c*, Potamides cinctus, Sow. (⅓); *d*, Limnæa longiscata, Brongn. (⅔).

Upper.—St. Gerand-le-Puy (Allier), Calcaire de Beauce in part, Sables de Fontainebleaux, Hamstead beds.	Appearance of the genera *Rhinoceros* (?), *Tapir*, *Palæochœrus*, shrew, *Plesiosorex*, *Mysarachne*, mole, musk-rat, *Lutrictis*, *Palæonycteris*, *Tetracus*. Disappearance of *Palæotherium*. Reign of *Hyopotamus* and *Anthracotherium*.
Middle.—Calcaire de Brie, &c.	Appearance of the genera *Cadurcotherium*, *Hyrachius*, *Entelodon*, *Anthracotherium*, *Dacrytherium*, *Chalicotherium*, *Tragulohyus*, *Lophiomeryx*, *Hyæmoschus* (?), *Gelocus*, *Dremotherium*, *Thereutherium*, dog (?), civet, marten, *Plesictis*, *Plesiogale*, *Ælurogale*, *Rhinolophus*, *Necrolemur*.
Lower. — Lacustrine gypsum of Paris, beds of Vaucluse, St. Hippolyte, Caton, Souvignargues, Bembridge beds.	Appearance of the genera opossum, *Chœropotamus*, *Tapirulus*, *Anoplotherium* (Fig. 435), *Eurytherium*, *Cainotherium*, *Anchilophus*, *Acotherulum*, *Cebochœrus*, *Xiphodon*, *Amphimeryx*, *Plesiarctomys*, dormouse (?), *Trechomys*, *Galethylax* (?), *Hyænodon*, *Adapis*. Reign of pachyderms. The carnivora have still partly marsupial characters.

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[1] For a list of British Oligocene mollusca, see Mr. R. B. Newton's volume cited on p. 966.

[2] A. Milne Edwards, 'Oiseaux Fossiles de la France,' 1867-71; Boyd Dawkins, 'Early Man in Britain,' p. 54.

[3] 'Les Enchaînements du Monde Animal,' 1878, p. 4.

§ 2. Local Development.

Britain.—Oligocene strata are confined to one small area in this country. They occur in the Hampshire basin and Isle of Wight, where resting conformably upon the top of the Eocene deposits, they consist of sands, clays, marls, and limestones, in thin-bedded alternations. They were accumulated partly in the sea, partly in brackish, and partly in fresh water. They were hence named by Edward Forbes "the fluvio-marine series," and were divided by him and Mr. Bristow into the following groups in descending order:[1]—

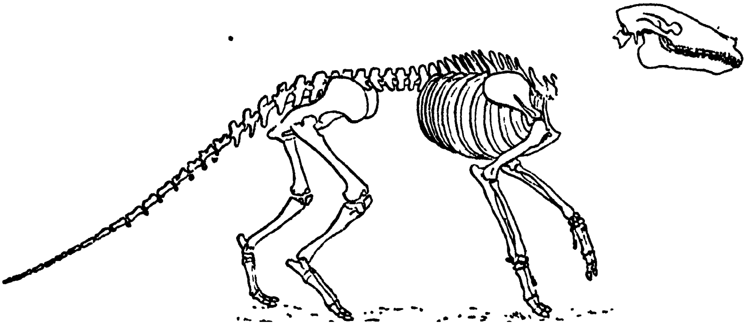

Fig. 435.—Anoplotherium commune, Cuv.

Hamstead Beds.—(*b*) Marine stage with *Corbula*, *Cytherea*, *Ostrea callifera*, *Voluta*, *Natica*, *Cerithium*. and *Melania*	31 ft.
(*a*) Fresh-water, estuarine, and lagoon stage, with *Unio*, *Cyrena*, *Cyclas*, *Paludina*, *Hydrobia*, *Melania*, *Planorbis*, *Cerithium* (rare), turtles, crocodiles, mammals, leaves and seeds	225 ,,
Bembridge Beds.—(*b*) Bembridge marls—a fresh-water, estuarine, and marine series of clays and marls, with *Viviparus* (*Paludina*), *Melania*, *Melanopsis*, *Limnæa*, *Cyrena*, *Unio*, *Ostrea*, *Cytherea*, *Mytilus*, *Nucula*	70-120 ,,
(*a*) Bembridge Limestone—full of fresh-water shells (*Limnæa*, *Planorbis*, &c.), and sometimes with many land-shells (*Bulimus*, *Achatina*, *Helix*, &c.)	15-25 ,,
Osborne Beds.—Marls, clays, shales, and limestones, with *Limnæa*, *Planorbis*, *Paludina*, *Melanopsis*, *Melania*, *Chara*, &c.	80-110 ,,
Headon Beds.—(*c*) Upper stage, consisting of fresh-water clays, marls, and bands of limestone, with *Potamomya*, *Limnæa*, *Cyrena*, *Unio*, *Potamides*, *Planorbis*, *Paludina*, *Bulimus*, &c.	40-60 ,,
(*b*) Middle stage, clays, sands, loams, and limestone, with brackish-water and marine fossils (*Cerithium*, *Planorbis*, *Limnæa*, *Melania*, *Natica*, *Neritina*, *Ostrea*, *Cyrena*, &c.)	30-126 ,,
(*a*) Lower stage, marls, clays, sandstones, and tufaceous limestones with fresh- and brackish-water shells (*Limnæa*, *Paludina*, *Planorbis*, *Cyrena*, *Potamomya*, &c.)	60-175 ,,

A large number of the marine mollusca of the Headon Beds range downwards into the Barton Clay, but about half are peculiar to the Oligocene series. Among the more abundant forms in the Isle of Wight are *Cytherea incrassata*, *Ostrea velata*, *O. flabellula*,

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[1] 'Geology of the Isle of Wight,' *Mem. Geol. Survey*, 2nd edit. p. 124. The grouping as here given has been slightly modified by Mr. C. Reid in the course of a re-survey of the Isle of Wight. The strata were formerly regarded as Upper Eocene.

Nucula headonensis, *Cerithium concavum*, *Melanopsis subfusiformis*, *Buccinum labiatum*, *Murex sexdentatus*, *Nerita aperta*, *Neritina concava*, *Ancillaria buccinoides*, *Melania muricata*, and several species of *Cancellaria*, *Natica*, *Pleurotoma*, and *Voluta*, with *Balanus unguiformis*. The estuarine and fresh-water strata are marked by species of *Potamomya* and *Cyrena*, while the purely fresh-water deposits are full chiefly of Limnæids belonging to the genera *Limnæa* and *Planorbis*, *L. longiscata* and *P. euomphalus* being perhaps the most abundant and conspicuous species ; *Paludina lenta* is also plentiful. Mr. Reid has remarked that every variation in the salinity of the water seems to have affected the molluscan fauna of the estuary in which these deposits were accumulated. When the water was quite fresh the pond snails flourished in abundance, and their remains were mingled with those of *Unio* and *Helix*. The gradual inroad of salt water is marked by the advent of *Potamomya*, *Cyrena*, *Cerithium* (*Potamides*), *Melania*, and *Melanopsis*, while the thoroughly marine fauna with volutes and cones shows when the sea had entirely replaced the fresh water.[1]

The Bembridge Limestone, one of the most conspicuous members of the Oligocene series in the Isle of Wight, is a remarkable example of a fresh-water limestone, full of fresh-water and terrestrial shells and nucules of *Chara*. The land-shells comprise tropical-looking gigantic species of *Bulimus* and *Achatina*. An interesting feature in the overlying Bembridge marls is the occurrence of a thin band from two inches to two feet in thickness of a fine-grained limestone like lithographic stone, containing many insect-remains with leaves and fresh-water shells. Some twenty genera of insects have been detected in it, including forms of coleoptera, hymenoptera, lepidoptera, diptera, neuroptera, orthoptera, and hemiptera.[2]

The Hamstead (formerly *Hempstead*) beds form an interesting close to the Oligocene series. They consist chiefly of fresh-water, estuarine, and lagoon deposits. But they pass upward into a group of marine strata of which only about 30 feet are now visible. Among the more abundant or peculiar of the shells in this marine band the following may be mentioned : *Ostrea cyathula*, *O. adlata* (both peculiar), *Cytherea Lyellii*, *Corbula pisum*, *C. vectensis*, *Cuma Charlesworthi*, *Voluta Rathieri*, *Cerithium plicatum*, *C. Sedgwickii*, *C. inornatum*, *Strebloceras*.[3]

Considerable interest attaches to the marine band forming the middle division of the Headon beds, as it serves for a basis of correlation between the English strata and their equivalents on the Continent. The band, so well seen in the Isle of Wight, occurs also at Brockenhurst and other places in the New Forest. It has yielded more than 230 species of fossils, almost all marine mollusks, but including also 14 species of corals. Of these organisms, a considerable proportion is common to the Lower Oligocene of France, Belgium, and Germany, and 22 species are found in the Upper Bagshot beds.[4]

The Oligocene or fluvio-marine series of the Hampshire basin has likewise yielded vertebrate remains such as characterise the corresponding deposits of the Continent. They include those of rays (*Myliobates*), snakes (*Palæoryx*), crocodiles, alligators, turtles (*Emys*, *Trionyx*, numerous species), and a cetacean (*Balænoptera*) ; while from the Bembridge beds have come the bones of a number of the characteristic mammals

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[1] C. Reid, 'Geology of the Isle of Wight,' *Mem. Geol. Survey*, p. 147.

[2] H. Woodward, *Quart. Journ. Geol. Soc.* xxxv. p. 342. C. Reid, 'Geology of the Isle of Wight,' p. 177.

[3] C. Reid, *op. cit.* p. 206.

[4] A. von Koenen, *Q. J. Geol. Soc.* xx. (1864) 97. Duncan, *op. cit.* xxvi. (1870) p. 66. J. W. Judd, *op. cit.* xxxvi. (1880) p. 137 ; xxxviii. (1882) p. 461. H. Keeping and E. B. Tawney, *op. cit.* xxxvii. (1881) p. 85 ; xxxix. (1883) p. 566. E. B. Tawney, *Geol. Mag.* 1883, p. 157. W. Keeping, *Geol. Mag.* 1883, p. 428. J. W. Elwes, *Brit. Assoc.* 1882. Sects. p. 539.

(*Anchilophus*, *Anthracotherium*, *Anoplotherium*, two species, *Palæotherium*, six or more species, *Chæropotamus*, *Dichodon*). The top of the fluvio-marine series in the Isle of Wight has been removed in denudation, so that the records of the rest of the Oligocene period have there entirely disappeared.

For many years it was customary to consider as Miocene certain plant-bearing strata, of which a small detached basin occurs at Bovey Tracey, Devonshire, but which are mainly distributed in the great volcanic plateaux of Antrim and the west of Scotland. These strata have since been regarded as equivalents of what are now termed Oligocene formations on the Continent. At the Bovey Tracey locality, which is not more than 80 miles from the Eocene leaf-beds of Bournemouth and the Isle of Wight, a small but interesting group of sand, clay, and lignite beds, from 200 to 300 feet thick, lies between the granite of Dartmoor and the Greensand hills, in what was evidently the hollow of a lake. From these beds, Heer of Zurich, who has thrown so much light on the Tertiary floras of both the Old World and the New, described about 50 species of plants, which, in his opinion, place this Devonshire group of strata on the same geological horizon with some part of the Molasse or Oligocene (Lower Miocene) groups of Switzerland. Among the species are a number of ferns (*Lastræa stiriaca*, *Pecopteris* (*Osmunda*) *lignitum*, &c.); some conifers, particularly *Sequoia Couttsiæ*, the matted débris of which forms one of the lignite beds; cinnamon-trees, evergreen oaks, custard-apples, eucalyptus, spindle-trees, a few grasses, water-lilies, and a palm (*Palmacites*). Leaves of oaks, figs, laurels, willows, and seeds of grapes have also been detected—the whole vegetation implying a subtropical climate.[1] More recently, however, Mr. Starkie Gardner has expressed the opinion that this flora is on the same horizon as that of Bournemouth, that is, in the Middle Eocene group.[2] If this view were established, the volcanic rocks of the north-west, with their leaf-beds, might be also relegated to the Eocene period. In the meantime, however, they are placed in the Oligocene series as probable equivalents of the brown-coal and molasse of the Continent.

The plateaux of Antrim, Mull, Skye, and adjacent islands are composed of successive outpourings of basalt, which are prolonged through the Faroe Islands into Iceland, and even far up into Arctic Greenland. In Antrim, where the great basalt sheets attain a thickness of 1200 feet, there occurs in them an intercalated band about 30 feet thick, consisting of tuffs, clays, thin conglomerate, pisolitic iron-ore and thin lignites. Some of these layers are full of leaves and fruits of terrestrial plants, with occasional insect-remains. According to the data collected by a Committee of the British Association, upwards of thirty species of plants have been obtained, including conifers (*Cupressinoxylon*, *Taxodium*, *Sequoia*, *Pinus*), monocotyledons (*Phragmites*, *Poacites*, *Iris*), dicotyledons (*Salix*, *Populus*, *Alnus*, *Corylus*, *Quercus*, *Fagus* (?), *Platanus*, *Sassafras*, *Acer*, *Andromeda*, *Viburnum*, *Aralia*, *Nyssa*, *Magnolia*, *Rhamnus*, *Juglans*, &c.)[3] In the west of Scotland the volcanic sheets attain still greater dimensions, reaching in Mull a thickness of 3000 feet, and there also including thin tuffs, leaf-beds, and coals. In Mull, Skye, and Antrim, the terraces of basalt, with occasional comparatively thin bands of tuff, form a noble example of the extravasation of great piles of lava without the formation of central cones or the discharge of much fragmentary matter (p. 258). They have been invaded by huge bosses of gabbro and of various granitoid rocks, which send veins into and alter the basalt. They are likewise traversed by veins of pitchstone, but more especially by prodigious numbers of basalt-dykes, which in Scotland have a prevalent W.N.W. and E.S.E. direction. The basalt-plain was channelled by rivers, and into the ravines thus eroded streams of pitchstone made their way (Scuir of Eigg), whence it is evident that the volcanic eruptions lasted during a protracted period.[1]

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[1] *Phil. Trans.* 1862.

[2] "British Eocene Flora," *Palæont. Soc.* 1879, p. 18. See also *Q. J. Geol. Soc.* xli. p. 82. The great uncertainty in the correlation of deposits by means of land-plants has been already referred to (pp. 660, 668, 959).

[3] W. H. Baily, *Brit. Assoc.* 1879, Rep. p. 162; 1880, p. 107; 1881, p. 152. On the north coast of Antrim, near Ballintoy, a band of tuff occurs about 150 feet thick. But in Ireland, as in Scotland, the tuffs take quite a subordinate place among the great piles of basalt.

France.—In the Paris basin, where a perfect upward passage is traceable from Eocene into Oligocene beds, the latter are composed of the following subdivisions:[2]—

Upper.	Helix-limestone of the Orléanais (*Helix*, *Planorbis*, &c.) Meulières de Montmorency—very hard siliceous, cellular, fossiliferous, fresh-water limestones employed for millstones (*Limnæa*, *Bythinia*, *Planorbis*, *Valvata*, *Chara*). This deposit is replaced towards the south by the fresh-water Calcaire de la Beauce, which is separable into a higher assise (Molasse du Gâtinais, sometimes 57 feet) consisting of green marl, siliceous sand, and calcareous sandstone passing into limestones (*Helix Moroguesi*, *H. aurelianus*, *H. Tristani*, *Planorbis solidus*, *Limnæa Larteti*, *Melania aquitanica*, &c.); and a lower, composed of limestone (*Limnæa Brongniarti*, *L. cornea*, *L. cylindrica*, *Helix Ramondi*, *Cyclostoma antiquum*, *Planorbis cornu*, *Potamides Lamarcki*, &c.) Grès de Fontainebleau. Sands, and hard siliceous sandstones. At the top of this subdivision there occurs at Ormoy, near Étampes, and elsewhere a band of calcareous marl full of marine fossils (*Cardita Bazini*, *Cytherea incrassata*, *Lucina Héberti*).
Middle.	Sables de Fontenay, Jeurre et Morigny, a thick accumulation of yellow ferruginous, generally unfossiliferous sands, covering a large area around Paris, and serving as a foundation for most of the new military forts of that locality. The "falun de Jeurre" contains many fossils (*Natica crassatina*, *Cerithium*, several species, *Cytherea incrassata*, *Avicula stampinensis*, &c.) Oyster-marls with *Ostrea longirostris*, *O. cyathula*, and *Corbula subpisum*. These pass into the Molasse d'Étrechy with *Cerithium plicatum*, *Melania semidecussata*, *Cytherea incrassata*, &c. Calcaire de la Brie, a lacustrine limestone with few fossils, *Limnæa cornea*, *Planorbis cornu*, *Chara*, &c. Green marls (Marnes à Cyrènes, glaises vertes), consisting of an upper mass of non-fossiliferous clay, and a lower group of fossiliferous laminated marls (*Cerithium plicatum*, *Psammobia plana*, *Cyrena convexa*).
Lower.	White marls (Marnes de Pantin) with *Limnæa strigosa*, *Planorbis planulatus*, *Nystia Duchasteli*. Supra-gypseous blue marls, with very few fossils (*Nystia plicata*). Lacustrine gypsum (*Gyps lacustre*). The highest and most important gypsum bed of the Paris basin (65 feet thick at Montmartre), with a remarkable prismatic structure, containing skeletons and bones of mammals (*Palæotherium*, *Anoplotherium*, *Xiphodon*), fragments of terrestrial wood, and a few terrestrial shells (*Helix*, *Cyclostoma*, &c.) This deposit is continuous with the marine gypsum underneath it (p. 978).

Geographical names have been assigned to the subdivisions of the Oligocene series in France, Belgium, Switzerland, and North Italy. The lowest member is called Tongrian, from Tongres, in Limbourg. Above it comes the Stampian, so named from Étampes, where it is typically developed. The uppermost group is known as Aquitanian, from its well-marked occurrence in Aquitania.

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[1] *Proc. Roy. Soc. Edin.* vi. (1867) p. 71; *Q. J. Geol. Soc.* xxvii. (1871) p. 280; *Trans. Roy. Soc. Edin.* xxxv. (1888) p. 21; *Q. J. Geol. Soc.* xlviii. (1892), Pres. Address, p. 162. Prof. Judd (*op. cit.* xxx. (1874) p. 220; xlv. (1889) p. 187), on the other hand, believes that there were five great volcanic cones in the Western Islands whence the streams of basalt flowed, and of which the mountains of Mull, Skye, &c., are the degraded ruins, and he regards the granitoid rocks as older than the others.

[2] Dollfus, *Bull. Soc. Géol. France*, 3e sér. vi. (1878) p. 293. The separation of an Oligocene series in the Paris basin is not admitted by many eminent French geologists.

The chief area of Oligocene strata in France lies between Paris and Orleans, where, spreading over a wide extent of country, they have been cut down by the streams so as in some cases to reveal the Eocene formations below them. The next area in importance lies far to the south-west (Aquitania), where the Lower Oligocene division (Tongrian of Belgium) is represented by a thick yellowish marine limestone (Calcaire à Astéries) with *Cerithium plicatum*, *Trochus Bucklandi*, *Natica crassatina*, &c. The Aquitanian stage is represented in Languedoc by marine marls with *Cerithium*, and marine conditions are indicated by the corresponding deposits in Provence.

But over the centre and south of France marine Oligocene deposits are generally absent, their place being taken by the marls, clays, and limestones of former lakes, which have preserved many of the terrestrial plants and animals of the period. One or more large sheets of fresh water lay in the heart of the country, surrounded by slopes clothed with a tropical flora. In these basins, a series of marls and limestones (1500 feet thick in the Limagne d'Auvergne) accumulated, from which have been obtained the remains of nearly 100 species of mammals, including some palæotheres, like those of the Paris basin, a few genera found also in the Mainz basin, crocodiles, snakes, numerous birds, and relics of the surrounding land-vegetation of the time. This water-basin appears to have been destroyed by volcanic explosions, which afterwards poured out the great sheets of lava, and formed the numerous cones or *puys* so conspicuous on the plateau of Auvergne. In the south of France, the Eocene groups are sometimes surmounted by lacustrine or brackish-water beds that point to the retirement of the nummulitic sea, and the advent of those more terrestrial and shallow-water conditions in which the Oligocene deposits were accumulated. In Provence, lacustrine beds (*Physa*, *Planorbis*, *Limnæa*, *Bulimus*, &c.) lie immediately upon the Upper Cretaceous rocks. At Aix these beds have long been noted for their abundant plants (*Callitris Brongniarti*, *Widdringtonia brachyphylla*, *Flabellaria lamanonis*, *Quercus*, *Laurus*, *Cinnamomum*), insects and mammals (*Palæotherium*, *Xiphodon*, *Anoplotherium*, *Chœropotamus*).

A singular and interesting development of Oligocene deposits in France, Switzerland, and southern Germany is found where they have filled up fissures and cavities of older, especially Upper Jurassic, limestones. One of the most remarkable of these occurrences is that of Quercy, now famous for the large number of remains of mammals which have been found there. These deposits are related to Tertiary strata in their vicinity, and never occur at a higher altitude than these strata. They consist of red clay and loam, with pisolitic limonite, becoming more phosphatic towards the bottom, where the phosphate of lime occurs in such quantity as to be profitably worked. Among the fossils recovered from these recesses are a number of shells (*Cyclostoma*, *Limnæa*, *Planorbis*) and species of *Palæotherium*, *Anoplotherium*, *Xiphodon*, *Hyænodon*, *Cainotherium*, *Amphitragulus*, &c. There have also been found the remains of a lemur (*Necrolemur antiquus*).[1]

Belgium.[2]—The succession of Oligocene beds in this country differs from that of France, and has received a different nomenclature, as follows :—

- Upper.—Wanting.
- Middle.
  - Rupelian.
    - Marine.
      - White sands of Bolderberg (*Bolderian*).
      - Clay of Boom and *Nucula* clay of Bergh—upwards of 40 species of fossils, including *Nucula compta* (*Leda lyelliana*), *Corbula subpisum* (= "Septarienthon" of northern Germany).
    - Fluvio-marine.
      - *Cerithium* sands of Vieux Jonc (Klein Spauwen) and *Pectunculus* sands of Bergh.
      - Henis clay. The fossils in this clay and the overlying sands are fluvio-marine (*Cyclostoma*, *Succinea*, *Pupa* ; *Planorbis*, *Limnæa*, *Neritina* ; *Cerithium*, *Melania*, *Bythinia*, *Cyrena*).

Filhol, *Ann. Sci. Géol.* 1876.

[2] Mourlon, 'Géol. Belg.'

Lower.	Tongrian.	Marine.	Sands of Neerepen. Sands of Grimmertingen. The Tongrian deposits contain an abundant marine fauna = the Egeln beds of Germany.

Germany.[1]—In northern Germany, while true Eocene deposits are wanting, the Oligocene groups are well developed both in their marine and fresh-water facies, and it was from their characters in that region that Beyrich proposed for them the term Oligocene. They occupy large more or less detached areas or basins, with local lithological and palæontological variations, but the following general subdivisions have been established:—

Upper.	Marine marls, clays, sands, sparingly distributed (Doberg, Hanover; Wilhelmshohe; Mecklenburg-Schwerin), with *Spatangus Hoffmanni, Terebratula grandis, Pecten Janus, P. decussatus, Arca Speyeri, Nassa pygmæa, Pleurotoma subdenticulata.* Brown-coal deposits of the Lower Rhine,[2] &c., with a flora of less tropical Indian and Australian type, and more allied to that of subtropical North America (*Acer, Cinnamomum, Cupressinoxylon, Juglans, Nyssa, Pinites, Quercus,* &c.) Some marine beds in this division contain *Terebratula grandis, Pecten Janus, P. Münsteri,* &c.
Middle.	Stettin (Magdeburg) sand and Septaria-clay (*Septarienthon*), with an abundant marine fauna (Foraminifera, *Pecten permistus, Leda deshayesiana, Nucula Chasteli, Pleurotoma scabra, Axinus obtusus, Fusus Koninckii, F. multisulcatus,* &c.) These beds are widely distributed in north Germany, and are usually the only representatives there of the Middle Oligocene deposits. In some places, however, a local brown-coal group occurs (*Alnus Kefersteini, Cinnamomum polymorphum, Populus Zaddachi, Taxodium dubium*).
Lower.	Egeln marine beds (*Ostrea ventilabrum, Pecten bellicostatus, Leda perovalis, Arca appendiculata, Cardita Dunkeri, Cardium Hausmanni, Cytherea Solandri, Cerithium lævum, Pleurotoma Beyrichi, P. subconoidea, Voluta decora, Buccinum bullatum,* &c., and corals of the genera *Turbinolia, Balanophyllia, Caryophyllia, Cyathina*).[3] Amber beds of Konigsberg, consisting of lignitiferous sands resting on marine glauconitic sands, near the base of which lies a band containing abundant pieces of amber. The latter, derived from several species of conifers, especially *Pinus succinifera,* have yielded a plentiful series, estimated at about 2000 species, of insects, arachnids, and myriapods, together with the fruits, flowers, seeds, and leaves of a large number of conifers (*Pinites, Pinus, Abies, Sequoia Langsdorfii, Widdringtonites, Libocedrus, Thuja, Cupressus, Taxodium*) and dicotyledons (*Quercus, Castanea, Fagus, Myrica, Polygonum, Cinnamomum, Geranium, Linum, Acer, Ilex, Rhamnus, Deutzia, Proteaceæ,* several genera, *Andromeda,* &c.)[4] The sands contain Lower Oligocene marine mollusca, sea-urchins, &c. Lower Brown-coal series—sands, sandstones, conglomerates, and clays with interstratified varieties of brown-coal (pitch-coal, earthy lignite, paper-coal, wax-coal, &c.), a single mass of which sometimes attains a thickness of 100 feet or more. These strata may be traced intermittently over a wide area of northern Germany. The flora of the brown-coal is largely composed of conifers (*Taxites, Taxoxylon, Cupressinoxylon, Sequoia,* &c.), but also with *Quercus, Laurus, Cinnamomum, Magnolia, Dryandroides, Ficus, Sassafras, Alnus, Acer, Juglans, Betula,* and palms (*Sabal, Flabellaria*). The general aspect of this flora most resembles that of the southern states of North America, but with relations to earlier tropical floras having Indian and Australian affinities.

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[1] Beyrich, *Monatsbericht. Akad. Berlin,* 1854, p. 640; 1858, p. 51. A. von Koenen, *Zeitsch. Deutsch. Geol. Ges.* xix. (1867) p. 23.

[2] For a popular account of the brown-coal of Germany see M. Vollert, 'Der Braunkohlenbergbau,' Halle, 1889, the "Festschrift" of the fourth Deutsche Bergmannstage in 1889.

[3] For detailed descriptions of the Lower Oligocene molluscan fauna of north Germany see Prof. A. von Koenen's elaborate monograph, *Abhand. Geol. Specialkart. Preuss.* x. (1889-92).

[4] 'Flora des Bernsteins,' vol. i. on the coniferæ, H. R. Goeppert, 1883; vol. ii. on the dicotyledons, Goeppert, A. Menge, and H. Conwentz, 1886.

In the Mainz basin some marine sands, clays, and marls in the lower part of its Tertiary deposits are referred to the Oligocene series, and are arranged as follows:—

Cerithium Beds.—Sandy and calcareous strata with brackish-water and land-shells (*Cerithium plicatum*, *Mytilus Faujasi*, *Helix*, &c.)
Cyrena marl and sand (*Cyrena semistriata*, *Cerithium plicatum*, *C. margaritaceum*, *Perna Sandbergeri*, &c.)
Septaria-clay with *Leda deshayesiana.*
Marine sand of Weinheim with *Ostrea callifera*, *Pectunculus obovatus*, *Cytherea incrassata*, *Natica crassatina.*

Switzerland.[1]—Nowhere in Europe do Oligocene strata play so important a part in the scenery of the land, or present on the whole so interesting and full a picture of the state of the continent when they were deposited, as in Switzerland. Rising into massive mountains, as in the well-known Rigi and Rossberg, they attain a thickness of several thousand feet. While they include proofs of the presence of the sea, they have preserved with marvellous perfection a large number of the plants which clothed the Alps, and of the insects which flitted through the woodlands. They form part of a great series of deposits which have been termed "Molasse" by the Swiss geologists. The Molasse was formerly considered to be entirely Miocene. The lower portions, however, are now placed on the same parallel with the Oligocene beds of the regions lying to the north, and consist of the following subdivisions:—

Lower Brown-coal or red Molasse (Aquitanian stage)—the most massive member of the Molasse, consisting of red sandstones, marls, and conglomerates (Nagelflue) with well-rounded mutually indented pebbles, resting upon variegated red marls. It contains seams of lignite, and a vast abundance of terrestrial vegetation.
Lower marine Molasse (Tongrian stage)—sandstone containing marine and brackish-water shells, among which are *Ostrea cyathula*, *O. longirostris*, *O. callifera*, *Cyrena semistriata*, *Cytherea incrassata*, *Pectunculus obovatus*, *Cerithium plicatum*, *Natica crassatina.* This division is well developed between Bâle and Berne.

By far the larger portion of these strata is of lacustrine origin. They must have been formed in a large lake, the area of which probably underwent gradual subsidence during the period of deposition, until in Miocene times the sea once more overflowed the area. We may form some idea of the importance of the lake from the fact that the deposits formed in its waters are upwards of 9000 feet thick. Thanks to the untiring labours of Professor Heer, we know more of the vegetation of the mountains round that lake, during Oligocene and Miocene time, than we do of that of any other ancient geological period. The woods were marked by the predominance of an arborescent subtropical vegetation, among which evergreen forms were conspicuous, the whole having a decidedly American aspect. Among the plants were palms of American type, the Californian coniferous genus *Sequoia*, alders, birches, figs, laurels, cinnamon-trees, evergreen oaks, with many other kinds.

A portion of the great Flysch formation of the Alps (which has been already referred to as partly Cretaceous, partly Eocene) is referred to the Oligocene series. It includes the shales of Glarus, long known for their fish-remains.

Vienna Basin.[2]—This area contains a typical series of Tertiary deposits, sometimes classed together as "Neogene." At the bottom lies an inconstant group of marls and sandstones (Aquitanian stage), containing occasional seams of brown-coal and fresh-water beds, but with intercalations of marine strata. The marine layers contain *Cerithium plicatum*, *C. margaritaceum*, &c. The brackish and fresh-water beds yield *Melania Escheri* and *Cyrena lignitaria*. Among the vertebrates are *Mastodon angustidens*, *M. tapiroides*, *Rhinoceros sansaniensis*, *Amphicyon intermedius*, *Anchitherium aurelianense*, and numerous turtles. These strata have suffered from the upheaval of the Alps, and may be seen sometimes standing on end. It is interesting also to observe that the subterranean movements east of the Alps culminated in the outpouring of enormous sheets of trachyte, andesite, propylite, and basalt in Hungary and along the flanks of the Carpathian chain into Transylvania. The volcanic action appears to have begun during the Aquitanian stage, but continued into later time. Further curious changes in physical geography are revealed by the other "Neogene" deposits of south-eastern Europe. Thus in Croatia, the Miocene marls, with their abundant land-plants, insects, &c., contain two beds of sulphur (the upper 4 to 16 inches thick, the under 10 to 15 inches), which have been worked at Radoboj. At Hrastreigg, Buchberg, and elsewhere, coal is worked in the Aquitanian stage in a bed sometimes 65 feet thick. In Transylvania, and along the base of the Carpathian Mountains, extensive masses of rock-salt and gypsum are interstratified in the "Neogene" formations.

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[1] Studer's 'Geologie der Schweiz,' vol. ii.; Heer's 'Urwelt der Schweiz,' 1865 (an English translation of which by Mr. W. S. Dallas appeared in 1876); 'Flora Fossilis Helvetiæ,' 1854-59; A. Favre, 'Description Géologique du Canton de Genève,' 1880, vol. i. p. 69.

[2] Suess, 'Der Boden von Wien,' 1860. Th. Fuchs, 'Erlauterungen zur Geol. Karte der Umgebungen Wiens,' 1873; and papers in *Zeitsch. Deutsch. Geol. Gesel.* 1877 (p. 653); *Jahrb. Geol. Reichsanst.* vols. xviii. *et seq.* Von Hauer's 'Geologie.'

Italy.—In the north of Italy strata assigned to the Oligocene series attain an enormous development, their total estimated thickness amounting to nearly 12,000 feet. They dovetail regularly with the Eocene below and the Miocene above, and are thus grouped by Prof. Sacco in the central part of the northern Apennines:—

Aquitanian Stage. 1000 metres.	A great thickness of grey and yellowish sands and occasional greyish marls, the marly character increasing northwards and eastwards. Fossils scarce.
Stampian Stage. 600 metres.	Grey marls more or less sandy and friable.
Tongrian Stage. 2000 metres.	A vast series of sandy marls, sands, conglomerates, and lenticles of lignite, with frequent nummulites (*N. intermedia*, *N. Fichteli*, *N. striata*), *Orbitoides*, fresh-water, brackish, and marine shells (*Ampullina crassatina*, *Potamides*, *Cyrena convexa*, &c.), *Anthracotherium magnum*, &c. Sometimes with greyish violet marls.
Sestian Stage. 20 metres.	A thin band of sandy marls with *Nummulites Fichteli*, *N. vasca*, *N. Boucheri*, *Orbitoides*, *Heterostegina*, &c.

North America.—Overlying the Jackson beds referred to on p. 981 a conformable group of strata known as the "Vicksburg beds" (Orbitoitic) occupies a narrow band in Alabama, Mississippi, and Louisiana, covers the greater part of Florida, and extends into Georgia and Texas. These strata in Mississippi are composed of a lower ferruginous rock (Red Bluff) 12 feet thick, and a set of crystalline limestones and blue marls (80 feet) resting on lignitic clays and lignites (20 feet). Among the fossils are *Ostrea gigantea*, *Pecten Poulsoni*, *Cardium diversum*, *Cardita planicosta*, *Panopæa oblongata*, *Cypræa lintea*, *Mitra mississippiensis*, *Cassidaria lintea*, *Conus sauridens*, *Madrepora mississippiensis*, *Flabellum Wailesii*, *Orbitoides Mantelli*. The last-named fossil is specially characteristic, and is found also in the West Indies, Malta, and the Turco-Persian frontier.

Section iii. Miocene.

§ 1. General Characters.

The European Miocene deposits reveal great changes in the geography of the Continent as compared with its condition in earlier Tertiary time.

So far as yet known, Britain and northern Europe generally, save an area over the site of Schleswig-Holstein and Friesland, were land during the Miocene period; but a shallow sea extended towards the south-east and south, covering the lowlands of Belgium and the basin of the Loire. The Gulf of Gascony then swept inland over the wide plains of the Garonne, perhaps even connecting the Atlantic with the Mediterranean by a strait running along the northern flank of the Pyrenees. The sea washed the northern base of the now uplifted Alps, sending, as in Oligocene time, a long arm into the valley of the Rhine as far as the site of Mainz, which then probably stood at the upper end, the valley draining southward instead of northward. The gradual conversion of salt into brackish and fresh water at the head of this inlet took place in Miocene time. From the Miocene firth of the Rhine, a sea-strait ran eastwards, between the base of the Alps and the line of the Danube, filling up the broad basin of Vienna, sending thence an arm northwards through Moravia, and spreading far and wide among the islands of south-eastern Europe, over the regions where now the Black Sea and Caspian basins remain as the last relics of this Tertiary extension of the ocean across southern Europe. The Mediterranean also still presented a far larger area than it now possesses, for it covered much of the present lowlands and foot-hills along its northern border, and some of its important islands had not yet appeared or had not acquired their present dimensions.

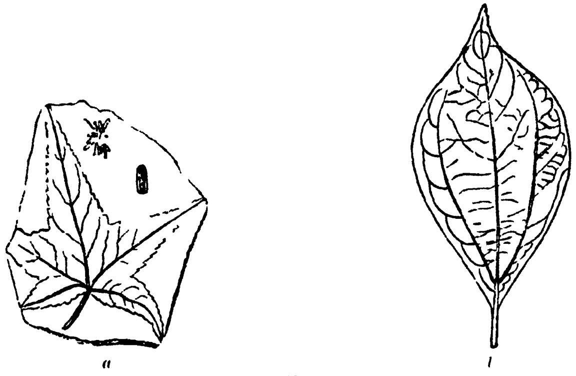

Fig 436 —Miocene Plants

a, Liquidambar europæum, Braun ([illegible]) *b*, Cinnamomum Buchi, Heer ([illegible])

Among the revolutions of the time not the least important in European geography was the continued uprise of the Alps by which the Eocene strata had been so convoluted and overthrown. These disturbances still went on in a diminished degree in Miocene time. One of their results was the restoration and extension of the wide lake or chain of lakes, over the northern or molasse region of Switzerland, in which the red molasse of Oligocene time had been deposited. The lacustrine deposits accumulated there have preserved with remarkable fulness a record of the terrestrial flora and fauna of the time.

The flora of the Miocene period (Figs. 436, 437) indicates a decidedly subtropical climate in the earlier part of that period in Europe, many of the plants having their nearest modern representatives in India and Australia.[1] Among the more characteristic genera are *Sabal*, *Phœnicites*, *Libocedrus*, *Sequoia*, *Myrica*, *Quercus*, *Ficus*, *Laurus*, *Cinnamomum*, *Daphne*, *Persaonia*, *Banksia*, *Dryandra*, *Cissus*, *Magnolia*, *Acer*, *Ilex*, *Rhamnus*, *Juglans*, *Rhus*, *Myrtus*, *Mimosa*, and *Acacia*. In the later part of the period, the climate, if we may judge from the character of the flora, had become less warm; for as the palms disappeared there came the flora of a more temperate type, including among the more frequent plants species of *Glyptostrobus*, *Betula*, *Populus*, *Carpinus*, *Ulmus*, *Laurus*, *Persea*, *Ilex*, *Podogonium*, and *Potamogeton*.[2]

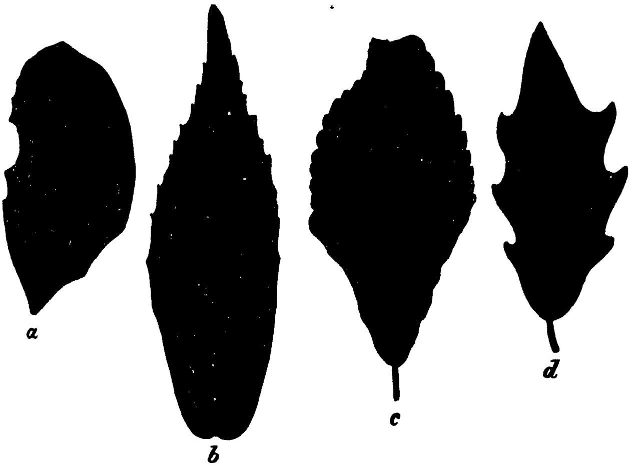

Fig. 437.—Miocene Plants.

a, Magnolia Inglefieldi (⅓); *b*, Rhus Meriani (nat. size).
c, Ficus decandolleana (½); *d*, Quercus ilicoides (⅔).

The fauna points to somewhat similar climatal conditions in Europe. There occur such molluscan genera as *Ancillaria*, *Buccinum*, *Cancellaria*, *Cassis*, *Cypræa*, *Mitra*, *Murex*, *Pyrula*, *Strombus*, *Terebra*, *Arca*, *Cardita*, *Cardium*, *Cytherea*, *Mactra*, *Ostrea*, *Panopæa*, *Pecten*, *Pectunculus*, *Spondylus*, *Tapes*, *Tellina*, &c. (Fig. 438). The mammalian forms present many points of contrast with those of older Tertiary time. Huge proboscideans now take a foremost place. Among the more important generic types of the time are the colossal *Mastodon* (Fig. 439) and *Deinotherium* (Fig. 440), the latter having tusks curving downwards from the lower law. With these are associated *Rhinoceros*, of which a hornless and a feebly horned species have been noted; *Anchitherium*, a small horse-like animal, about as big as a sheep, surviving from earlier Tertiary time; *Macrotherium*, a huge ant-eater; *Dicroceras*, a deer allied to the living muntjak of eastern Asia; *Hyotherium*, an animal nearly related to the hog. A number of living genera likewise made their entry upon the scene, such as the hog, otter, antelope, beaver, and cat. Some of the most formidable animals were the sabre-toothed tigers (*Machairodus*), and the earliest form of bear (*Hyænarctos*). The Miocene forests were also tenanted by apes, of which several genera have been detected. Of these, *Pliopithecus* was probably allied to the anthropoid apes; *Dryopithecus* (Fig. 441) was regarded

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[1] Heer, 'Urwelt der Schweiz'; 'Flora Fossilis Helvetiæ.'

[2] Saporta, 'Monde des Plantes,' p. 272.

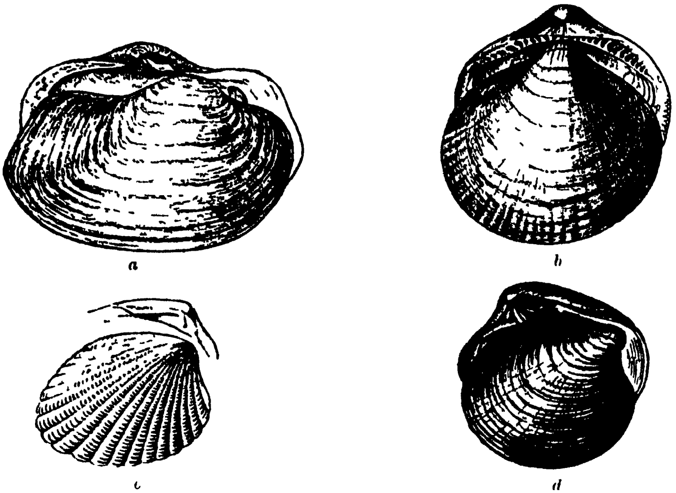

Fig. 438.—Miocene Mollusks.
a, Panopæa Faujasii, Men. de la Groye (⅓), *b*, Pectunculus glycimeris (P. pilosus), Linn. (⅓); *c*, Cardita affinis, Duj.; *d*, Tapes gregaria, Partsch. (½).

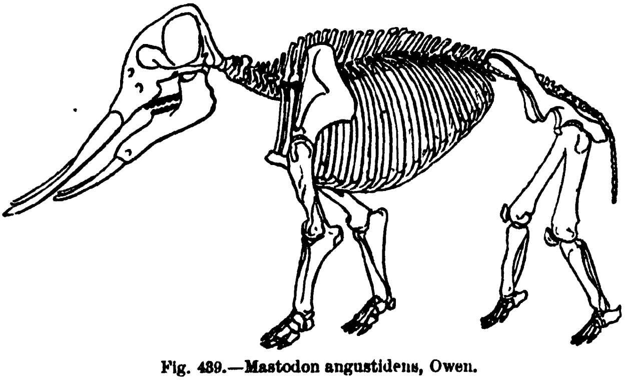

Fig. 439.—Mastodon angustidens, Owen.
Reduced from restoration by M. Gaudry.[1]

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[1] For a restoration of *M. americanus*, see Marsh, *Amer. Journ. Sci.* xliv. (1892) p. 350.

by Owen as allied to the living gibbons, but Gaudry regards it as an anthropoid form, and as the only one yet found fossil which can be compared with man;[1] *Oreopithecus* is supposed to have had affinities with the anthropoid apes, macaques, and baboons; and a species of *Colobus* is found in Wurtemburg.[2]

Among the discoveries in western America, which have thrown so much light upon the history of vertebrate life, mention should be made here of the remarkable assemblage of mammals disinterred from the base of the vast lacustrine Miocene formations on the eastern flanks of the Rocky Mountains. The Brontotheridæ or Titanotheridæ, the largest of these animals, formed a distinct family more nearly allied to the living rhinoceros than to any other recent form.

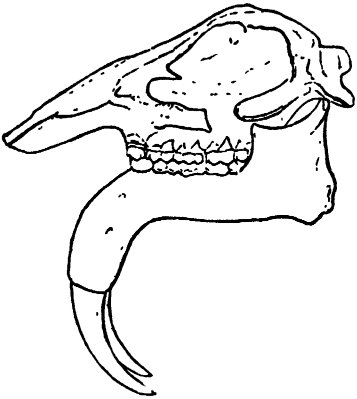

Fig. 440.—Deinotherium giganteum, Kaup., reduced.

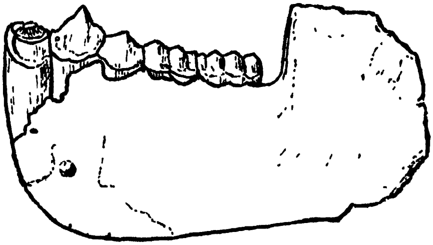

Fig. 441.—Jaw of Dryopithecus Fontani, Gaudry (⅔).

Considerable uncertainty must be admitted to rest upon the correlation of the later Tertiary deposits in different parts of Europe. In many cases, their stratigraphical relations are too obscure to furnish any clue, and their identification has therefore to be made by means of fossil evidence. But this evidence is occasionally contradictory. For example, the remarkable mammalian fauna described by M. Gaudry from Pikermi in Attica (*postea*, p. 1019) has so many points of connection with the recognised Miocene fauna of other European localities, that this observer classed it also as Miocene. He has pointed out, however, that in a shell-bearing bed underlying the ossiferous deposit of Pikermi some characteristic Pliocene species of marine mollusca occur. Remembering how deceptive sometimes is the chronological evidence of terrestrial faunas and floras, (*ante*, pp. 660, 668) we may here take marine shells as our guide, and place the Pikermi beds in the Pliocene series.

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[1] *Mem. Soc. Géol. France* (3), i. fasc. 1. (1890).

[2] Gaudry, 'Les Enchaînements,' p. 306; Boyd Dawkins, 'Early Man in Britain,' p. 57.

§ 2. Local Development.

France.—True Miocene deposits are not known to occur in Britain. In France, however, in the district of Touraine, traversed by the rivers Loire, Indre, and Cher, there occurs a group of shelly sands and marls, which, as far back as 1833, was selected by Lyell as the type of his Miocene subdivision. These strata occur in widely extended but isolated patches, rarely more than 50 feet thick, and are better known as "Faluns," having long been used as a fertilising material for spreading over the soil. They present the characters of littoral and shallow-water marine deposits, consisting sometimes of a kind of coarse breccia of shells, shell-fragments, corals, polyzoa, &c., occasionally mixed with quartz-sand, and now and then passing into a more compact calcareous mass or even into limestone. Along a line that may have been near the coast-line of the period, a few land and fresh-water shells, together with bones of terrestrial mammals, are found, but, with these exceptions, the fauna is throughout marine. Among the fossils are numerous corals, and upwards of 300 species of mollusks, of which the following are characteristic: *Pholas Dujardini*, *Venus clathrata*, *Ostrea crassissima*, *Pecten striatus*, *Cardium turonicum*, *Cardita affinis*, *Trochus incrassatus*, *Cerithium intradentatum*, *Turritella Linnæi*, *T. bicarinata*, *Pleurotoma tuberculosa*, with species of *Cypræa*, *Conus*, *Murex*, *Oliva*, *Ancillaria*, and *Fasciolaria*. This assemblage of shells indicates a warmer climate than that of southern Europe at the present time. The mammalian bones include the genera *Mastodon*, *Rhinoceros*, *Hippopotamus*, *Chæropotamus*, deer, &c., and extinct marine forms allied to the morse, sea-cow, and dolphin. Similar faluns, perhaps slightly later in age, are found in Anjou and Maine.

In the region of Bordeaux and the plains of the Garonne southward to the base of the Pyrenees, a large area is overspread with Oligocene deposits, equivalents of the younger Tertiary series of the Paris basin. Above these fresh-water and marine beds lie patches of faluns like those of Touraine, containing a similar assemblage of marine fossils. Other marine deposits of Miocene age are found running up the valley of the Rhone. But in the south and south-east of France the Miocene strata are mainly of lacustrine origin, sometimes attaining a thickness of 1000 feet, as in the important series of limestones and marls of Sansan and Simorre, whence remains of numerous interesting mammalia have been obtained. Among these remains are *Deinotherium giganteum*, *Mastodon angustidens*, *M. tapiroides*, *M. pyrenaicus*, *Rhinoceros Schleiermacheri*, *R. sansaniensis*, *R. brachypus*, *Anchitherium aurelianense*, *Anthracotherium onoideum*, *Amphicyon giganteus*, *Machairodus cultridens*, *Helladotherium Duvernoyi*, *Dicroceras elegans*, and several apes and monkeys (*Pliopithecus*, *Dryopithecus*).

The Miocene deposits of France, though scattered in isolated patches, have been grouped into three stages in the following ascending order: 1st, Lhangian—sands and marls (l'Orléanais, Sologne, &c.), limestones (Sansan, Simorre); 2nd, Helvetian—shelly sands, faluns (Touraine, Anjou, Aquitaine); 3rd, Tortonian—marls with *Helix turonensis*.

Belgium.—In this country, the upper Oligocene strata of Germany are absent. In the neighbourhood of Antwerp certain black, grey, or greenish glauconitic sands

("Black Crag," Bolderian and Anversian), of which the palæontological characters were at one time supposed to present a mingling of Miocene and Pliocene affinities. These deposits were accordingly termed by some geologists Mio-pliocene. They consist of gravelly sands at the base, containing cetacean bones (*Heterocetus*), fish-teeth, *Ostrea navicularis*, *Pecten Caillaudi*, &c. They are followed by sands with *Pectunculus glycimeris* (*pilosus*), and these by sands with *Panopæa Faujasii* (*Menardi*). More recent research has shown that the lower part of this series of deposits is Miocene, and is separated by a break and erosion-line from the superincumbent Diestian group which is referable to the Pliocene series.

Germany.—Certain deposits of dark clay and sand spread over parts of the north-west of Germany containing *Conus Dujardini*, *C. antediluvianus*, *Fusus festivus*, *Isocardia cor*, *Pectunculus glycimeris* (*pilosus*), *Limopsis aurita*, &c., and are referred to the Miocene formations. These are doubtless a prolongation of the Belgian series. Elsewhere the deposits referable to this geological period are lacustrine or fluviatile in origin, and are especially marked by the occurrence in them of brown-coals which are worked.

In the Mainz Tertiary basin an important series of marine, brackish, and fresh-water deposits occurs, which has been arranged by Fridolin Sandberger as follows:[1]—

Pliocene—
  Uppermost brown-coal.
  Bone-sand of Eppelsheim (Deinotherium sand), see p. 1017.
Miocene—
  Clay, sand, &c., with leaves.
  Limestone with *Litorinella* (*Hydrobia*) *acuta*, *Helix moguntina*, *Planorbis*, *Dreissena*, &c.
  Corbicula beds with *Corbicula Faujasii*, *Hydrobia inflata*, *H. acuta*.
  Cerithium limestone and land-snail limestone.
  Sandstone with leaves (*Cinnamomum*, *Sabal*, *Quercus*, *Ulmus*).
Oligocene (see p. 992).

The lower Miocene beds of this area present much local variation, some being full of terrestrial plants, some containing fresh-water, and others brackish-water and marine shells, indicating the final shoaling of the Oligocene fjord which ran down the upper valley of the Rhine as far as Mainz. Among the plants are species of *Quercus*, *Ulmus*, *Planera*, *Cinnamomum*, *Myrica*, *Sabal*, &c. The land-snail limestone contains numerous species of *Helix* and *Pupa*, with *Cyclostoma* and *Planorbis*. The *Cerithium* limestone contains marine or estuarine shells, as *Perna*, *Mytilus*, *Cerithium* (*C. Rahtii*, *C. plicatum*), *Nerita*. Among the various strata, bones of some of the terrestrial mammals of the time occur (*Microtherium*, *Palæomeryx*). The Litorinella limestone, the most extensive bed in the series, is composed of limestone, marl, and shale, sometimes made up of *Hydrobia* (*Litorinella*) *acuta*, in other places of *Dreissena* (*Tichogonia*, *Congeria*) *Brardi*, or *Mytilus Faujasii*. Abundant land and fresh-water shells also occur. Of greater interest are the mammalian remains, which include those of *Deinotherium giganteum*, *Palæomeryx*, *Microtherium*, and *Hipparion* (*Hippotherium*). The flora of the higher parts of the Miocene series includes several species of oak and beech, also varieties of evergreen oak, magnolia, acacia, styrax, fig, vine, cypress, and palm.

Vienna Basin.[2]—Overlying the Aquitanian stage (p. 993), where that is present, in other cases resting unconformably upon older Tertiary rocks, come the younger Tertiary or Neogene deposits of the Vienna basin—a large area comprising the vast depression between the foot of the eastern Alps near Vienna, the base of the plateau of Bohemia and Moravia, and the western slopes of the Carpathians. This tract communicated with the open Miocene sea by various openings in different directions. Its Miocene deposits are composed of two chief divisions or stages as follows, in descending order:—

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[1] 'Untersuchungen uber das Mainzer Tertiarbecken,' 1853; 'Die Conchylien des Mainzer Tertiärbeckens,' 1863.

[2] T. Fuchs, *Z. Deutsch. Geol. Ges.* 1877, p. 653; Hornes and Partsch, 'Die Fossil. Mollusken Tertiar. Beckens,' Wien, 1851-70; Ettingshausen, 'Die Tertiarfloren d. Oesterr. Monarchie,' 1851; Von Hauer's 'Geologie,' p. 617.

Sarmatian or Cerithium Stage.—Sandstones passing into sandy limestones and clays, or "Tegel" (the local name for a calcareous clay). According to Fuchs, the following subdivisions occur around Vienna:—

Upper Sarmatian Tegel, or Muscheltegel—distinguishable from the Hernals Tegel below by an abundance of shells (*Tapes gregaria*, *Ervilia*, *Cardium*, &c.), 295 feet.

Cerithium-sand—a yellow, abundantly shell-bearing, quartz-sand—the main source of water-supply at Vienna, where it is sometimes nearly 500 feet thick.

Hernals Tegel—sand and gravel, with *Cerithium*, *Rissoa*, *Paludina*, remains of turtles, fish, and land plants.

The Sarmatian stage is characterised by the prodigious number of individuals of a comparatively small number of species of shells, of which some of the most characteristic forms are *Tapes gregaria* (Fig. 438), *Mactra podolica*, *Ervilia podolica*, *Cerithium pictum*, *C. rubiginosum*, *Buccinum baccatum*, *Trochus podolicus*, *Murex sublævatus*. The general character of the fauna is that of a temperate climate, and is strongly contrasted with that of the Mediterranean stage in the absence of the affinities with tropical or sub-tropical forms, and even with those of the present Mediterranean, and on the other hand in some curious analogies with the living fauna of the Black Sea. Corals, echinoderms, bryozoa, foraminifera are absent or very rare, and the suggestion has been made that the change of the earlier Mediterranean fauna into that of the Sarmatian stage points to a gradual diminution of the salinity of the waters of the Vienna basin, as has happened with the existing Black Sea. The terrestrial flora is characterised by some plants that survived from the earlier or Mediterranean stage; but palms are entirely absent, and the American element in the flora is no longer surpassed by the preponderance of Asiatic types.

Mediterranean or Marine Stage.—A group of strata varying greatly from place to place in petrographical characters, with corresponding differences in fossil contents. Among the more important types of rock the following may be named:

Leithakalk, a limestone often entirely composed of organisms, and especially of reef-building corals, also bryozoa, foraminifera, echini (large clypeasters, &c.), large oysters (*Pecten latissimus* is specially characteristic), bones of mammals, and sharks' teeth. The Leithakalk passes frequently into sandy and marly beds, and into massive conglomeratic deposits (Leithakalk-schotter or conglomerate).

Tegel of Baden—fine blue clay, richly charged with shells, especially gasteropods (*Pleurotoma*, *Cancellaria*, *Fusus*, &c.) and foraminifera.

Marl of Gainfahren, Grinzing, Nussdorf, &c.—more calcareous than the Baden Tegel.

Sand of Potzleinsdorf—a fine loose sand with *Tellina*, *Psammobia*, and many other lamellibranchs.

Sandstone of Sievering with many lamellibranchs, especially pectens and oysters.

These various strata are believed to represent different conditions of deposit in the area of the Vienna basin during the time of the Mediterranean stage. With them are grouped certain fresh-water beds (brown-coals, &c.), found along the margin of the basin, which are supposed to mark some of the terrestrial accumulations of the period.

The characteristically marine fauna of this stage is abundant and varied. It presents as a whole a more tropical character than that of the Sarmatian stage above. Of its molluscan genera (of which more than 1000 species have been described) some of the more characteristic are: *Conus*, *Oliva*, *Cypræa*, *Voluta*, *Mitra*, *Cassis*, *Strombus*, *Triton*, *Murex*, *Pleurotoma*, *Cerithium*, *Spondylus*, *Pinna*, *Pectunculus*, *Cardita*, *Venus*. A number of the species still live in the Mediterranean, or in the seas off the West Coast of Africa. The abundant flora, with its various kinds of palms, had also a tropical aspect, somewhat like those of India and Australia.

Switzerland.—Immediately succeeding the strata described on p. 992, as referable to the Oligocene series, come the following groups in descending order:—

Upper fresh-water Molasse and brown-coal (Oeningen or Tortonian stage), consisting of sandstones, marls, and limestones, with a few lignite-seams and fresh-water shells, and including the remarkable group of plant- and insect-bearing beds of Oeningen.

Upper marine or St. Gallen Molasse (Helvetian stage)—sandstones and calcareous conglomerates, with 37 per cent of living species of shells, which are to be found partly in the Mediterranean, and partly in tropical seas: *Pectunculus glycimeris* (*pilosus*), *Panopæa Faujasii* (*Menardi*), *Conus ventricosus*, &c.

Lower fresh-water or Grey Molasse (Lhangian stage, Mayencian)—sandstones with abundant remains of terrestrial vegetation, and containing also an intercalated marine band with *Cerithium lignitarum*, *Murex plicatus*, *Venus clathrata*, *Ostrea crassissima*, &c.

In the Oeningen beds, so gently have the leaves, flowers, and fruits fallen, and so well have they been preserved, we may actually trace the alternation of the seasons by the succession of different conditions of the plants. Selecting 482 of those plants which admit of comparison, Heer remarks that 131 might be referred to a temperate, 266 to a sub-tropical, and 85 to a tropical zone. American types are most frequent among them; European types stand next in number, followed in order of abundance by Asiatic, African, and Australian. Great numbers of insects (between 800 and 900 species) have been obtained from Oeningen. Judging from the proportions of species found there, the total insect fauna may be presumed to have been then richer in some respects than it now is in any part of Europe. The wood-beetles were specially numerous and large. Nor did the large animals of the land escape preservation in the silt of the lake. We know, from bones found in the Molasse, that among the inhabitants of that land were species of tapir, mastodon, rhinoceros, and deer. The woods were haunted by musk-deer, apes, opossums, three-toed horses, and some of the strange, long-extinct Tertiary ruminants, akin to those of Eocene times. There were also frogs, toads, lizards, snakes, squirrels, hares, beavers, and a number of small carnivores. On the lake, the huge *Deinotherium* floated, mooring himself perhaps to its banks by the two strong tusks in his under jaw. The waters were likewise tenanted by numerous fishes, of which 32 species have been described (all save one referable to existing genera), crocodiles, and chelonians.

Italy.—The enormous Aquitanian stage of Liguria (p. 993) is followed by (1) blue homogeneous marine marls, reaching a depth of nearly 2000 feet and marked by the abundance of pteropods, also *Ostrea neglecta*, *Cassidaria vulgaris*, and *Aturia aturi*. This stage, called by Mayer "Langhien," is paralleled with that of Mainz. It is surmounted by (2) the Helvetian stage (3280 feet), composed of three divisions: a lower (1000 to 1300 feet) composed of shaly marls rich in *Vaginella*, *Cleodora*, &c.; a middle (700 to 750 feet) consisting of yellowish sandy molasse with bryozoa, *Pecten ventilabrum*, *Terebratula miocenica*, &c.; and an upper (more than 300 feet) composed of beds of conglomerate and nullipores, with oysters, pectens, &c. The Tortonian stage (3) is made up of blue marls (650 feet), forming a remarkably constant band, with a profusion of *Pleurotomaria* and species of *Conus*, *Natica*, *Ancillaria*, &c.[1]

Greenland.[2]—One of the most remarkable geological discoveries of modern times has been that of Tertiary plant-beds in North Greenland. Heer has described a flora extending at least up to 70° N. lat., containing 137 species, of which 46 are found also in the central European Miocene basins. More than half of the plants are trees, including 30 species of conifers (*Sequoia*, *Thujopsis*, *Salisburia*, &c.), besides beeches, oaks, planes, poplars, maples, walnuts, limes, magnolias, and many more. These plants grew on the spot, for their fruits in various stages of growth have been obtained from the deposits. From Spitzbergen (78° 56′ N. lat.) 136 species of fossil plants have been named by Heer. But the latest English Arctic expedition brought to light a bed of coal, black and lustrous like one of the Palæozoic fuels, from 81° 45′ N. lat. It is from 25 to 30 feet thick, and is covered with black shales and sandstones full of land-plants. Heer notices 30 species, 12 of which had already been found in the Arctic Miocene zone. As in Spitzbergen, the conifers are most numerous (pines, firs, spruces, and cypresses), but there occur also the Arctic poplar, two species of birch, two of hazel, an elm, and a viburnum. In addition to these terrestrial trees and shrubs, the lacustrine waters of the time bore water-lilies, while their banks were clothed with reeds and sedges. When we remember that this vegetation grew luxuriantly within 8° 15′ of the North Pole, in a region which is now in darkness for half of the year, and almost continuously buried under snow and ice, we can realise the difficulty of the problem in the distribution of climate which these facts present to the geologist.

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[1] C. Mayer, *Bull. Soc. Géol. France* (3) v. p. 288. F. Sacco, 'Il Bacino Terziario del Piemonte,' Turin, 1889.

[2] Heer, "Flora Fossilis Arctica," in seven vols. 1868-83; *Q. J. Geol. Soc.* 1878, p. 66; Nordenskiöld, *Geol. Mag.* iii. (1876) p. 207. In this paper sections, with lists of the plants found in Spitzbergen, are given.

India.—The Oligocene and Miocene deposits of Europe have not been satisfactorily traced in Asia. As already stated, the upper part of the massive Nari group of Sind may represent some part of these strata. The Nari group is succeeded in the same region by the Gaj group, 1000 to 1500 feet thick, chiefly composed of marine sands, shales, clays with gypsum, sandstones, and highly fossiliferous bands of limestone. The commonest fossils are *Ostrea multicostata*, and the urchin *Breynia carinata*. Some of the species are still living, and the whole aspect of the fauna shows it to be later than Eocene time. The uppermost beds are clays with gypsum, containing estuarine shells and forming a passage into the important Manchhar strata. The Manchhar group of Sind consists of clays, sandstones, and conglomerates, sometimes probably 10,000 feet thick, divisible into two sections, of which the lower may possibly be Miocene, while the upper may represent the Pliocene Siwalik beds (p. 1020). As a whole, this massive group of strata is singularly unfossiliferous, the only organisms of any importance yet found in it being mammalian bones, of which 22 or more species have been recognised. All of these occur in the lower section of the group. They include the carnivore *Amphicyon palæindicus*, three species of *Mastodon*, one of *Deinotherium*, two of *Rhinoceros*, also one of *Sus*, *Chalicotherium*, *Anthracotherium*, *Hyopotamus*, *Hyotherium*, *Dorcatherium* (two), *Manis*, a crocodile, a chelonian, and an ophidian.[1]

North America.—Overlying the Eocene formations (p. 981), and following in a general way their trend, but sometimes with a slight unconformability, a belt of marine deposits, referred to the Miocene period, runs along the Atlantic border through the states of New Jersey, Delaware, Maryland, Virginia, North and South Carolina, and Georgia. These strata ("Yorktown" and "Sumpter" groups of Dana) have recently been classified by A. Heilprin as follows: 3, Upper or Carolinian (North and South California, Sumpter beds). 2, Middle or Virginian (Virginia and newer group in Maryland; Yorktown beds, in part); one of the most interesting members of this subdivision is the "Richmond earth," a diatomaceous deposit, sometimes 30 feet thick, lying near the base of the group. 1, Lower or Marylandian (older Miocene deposits of Maryland and possibly lower beds in Virginia; Yorktown beds, in part).[2]

Westward, in the Upper Missouri region, and across the Rocky Mountains into Utah and adjacent territories, strata assigned to the same geological period have been termed the White River group. They were laid down in great lakes, and attain thicknesses of 1000 to 2000 feet. The organic remains of these ancient lakes, so well studied by Leidy, Marsh, and Cope, embrace examples of three-toed horses (*Anchitherium*, *Miohippus*, *Mesohippus*), tapir-like animals, differing from those of the older Tertiary strata (*Lophiodon*); hogs as large as rhinoceroses (*Elotherium*); true rhinoceroses (*Rhinoceros*, *Hyracodon*, *Diceratherium*), huge elephantoid creatures allied to the Deinoceras and tapir (*Brontotherium*, *Titanotherium*); also even-toed ruminant ungulates, some allied to the hog (*Oreodonts*), others like stags (*Leptomeryx*) and camels (*Poëbrotherium*); carnivores (*Canis*, *Amphicyon* (*Daphænus*), *Machairodus*, *Hyænodon*), several of which are generically identical with European Tertiary wolves, lions, and bears. Among the smaller forms are the remains of the earliest known beavers (*Palæocastor*).

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[1] Medlicott and Blanford's 'Geology of India,' p. 472.

[2] A. Heilprin, as cited on p. 981.

Australia.—Tertiary deposits are extensively developed in various parts of the Australian Continent. In Victoria they cover nearly half of the colony, and are there capable of subdivision into an older and newer series. The older series is believed to be later than Eocene and to be possibly of Oligocene or older Miocene age. It consists principally of blue or grey clays with septarian nodules, rich in fossils, among which gigantic forms of Volutes and Cowries are conspicuous. Later than these clays are certain (Miocene) deposits indicating marine, lacustrine, and terrestrial conditions, with the existence of contemporaneous volcanic activity towards the end of the series. The marine rocks consist mainly of calcareous sandy strata and limestones, with *Cellepora*, *Spatangus*, *Terebratula*, &c. The lacustrine deposits are clays and lignites, and the fluviatile materials consist of gravels and sands which are often auriferous. Great sheets of basalt, forming the older volcanic series, have been poured over these various accumulations, which are sometimes 300 feet thick. A large series of plants, mollusks, fishes, and marine mammals has been obtained from the Miocene series of Victoria.[1]

New Zealand.—Rocks assigned to Miocene time in New Zealand are divisible into: 1st, A lower series, consisting of calcareous and argillaceous strata widely spread over the east and central part of the North Island and both sides of the South Island. They can be traced to a height of 2500 feet above the sea. Marine shells abound in them, including 55 species which are found among the 450 shells that now live in the adjacent seas. Some of the most notable fossils are *Dentalium irregulare*, *Pleurotoma awamoaensis*, *Conus Traillì*, *Turritella gigantea*, *Buccinum Robinsoni*, *Cucullæa alta*. In some places thick deposits of an inferior kind of brown-coal occur in this subdivision. 2nd, An upper series composed of littoral or sub-littoral accumulations of sand, gravel, and clay. They have yielded 120 recent species of shells, and 25 species which appear now to be extinct. Specially characteristic are *Ostrea ingens*, *Murex octagonus*, *Fusus triton*, *Struthiolaria cingulata*, *Chione assimilis*, *Pecten gemmulatus*.[2]

Section iv. Pliocene.

§ 1. General Characters.

The tendency towards local and variable development, which is increasingly observable as we ascend through the series of Tertiary deposits, reaches its culmination in those to which the name of Pliocene has been given. The only European area, in which Pliocene strata attain any considerable dimensions as rock-masses, is in the basin of the Mediterranean, especially along both sides of the Apennine chain and in Sicily. In that region, reaching a thickness of 1500 feet or more, they were accumulated during a slow depression of the sea-bottom, and their growth was brought to an end by the subterranean movements which culminated in the outbreak of Etna, Vesuvius, and the other late Tertiary Italian volcanoes, and in the uprise of the land between the base of the Apennines and the sea on either side of the peninsula. Elsewhere the marine Pliocene deposits of Europe, local in extent and variable in character, reveal the beds of shallow seas, the elevation of which into land completed the outlines of the Continent at the close of Tertiary time. Thus these waters covered the south and south-east of England, spreading over Belgium and a small part of northern France, but leaving the rest of northern and western Europe as dry land. Here and there, in south-eastern Europe, evidence exists of the gradual isolation of portions of the sea into basins, somewhat like those of the Aralo-Caspian depression, with a brackish or less purely marine fauna. In some portions of these basins, however, as in the Karabhogas Bay of the existing Caspian Sea, such concentration of the water took place as to give rise to extensive accumulations of salt and gypsum. In a few localities, fluviatile and lacustrine deposits of the Pliocene period have been preserved, from which numerous remains of terrestrial vegetation and mammals have been obtained.

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[1] R. A. F. Murray, 'Geology and Physical Geography of Victoria,' 1887. M'Coy, 'Prodromus of Victorian Palæontology.'

[2] Hector, 'Handbook on New Zealand,' p. 27.

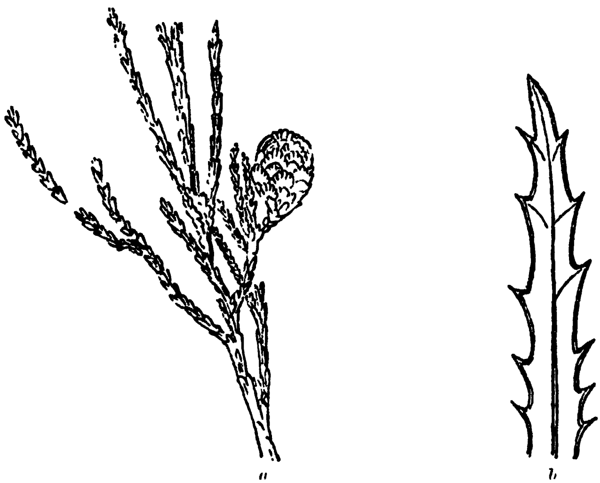

Fig. 442.—Pliocene Plants.
a, Glyptostrobus europæus, Brongn. (½); *b*, Hakea exalata, Heer.

The Pliocene flora is transitional between the luxuriant evergreen and sub-tropical vegetation of the Miocene period and that of modern Europe. From the evidence of the deposits in the upper part of the valley of the Arno, above Florence, it is known to have included species of pine, oak, evergreen-oak, plum, plane, alder, elm, fig, laurel, maple, walnut, birch, buckthorn, hickory, sumach, sarsaparilla, sassafras, cinnamon, glyptostrobus, taxodium, sequoia, &c.[1] The researches of Count de Saporta have shown that the flora of Meximieux, near Lyons, comprised species of bamboo, liquidambar, rose-laurel, tulip-tree, maple, ilex, glyptostrobus, magnolia, poplar, willow, and other familiar trees.[2] The forests of that part of Europe during Pliocene time conjoined some of the more striking characters of those of the present Canary Islands, of North America, and of Caucasian and eastern Asia, including Japan. There is evidence, however, that a marked refrigeration of climate was in gradual progress, during which the plants, such as the palms, especially characteristic of warmer latitudes, one by one retreated from the European region, or lingered only on its southern borders. In England, towards the end of the Pliocene period, the climate, if we may judge of it from the plants preserved in the Cromer Forest-bed, had come to be very much what it is to-day. Among the vegetable remains found in that deposit are those of many of the familiar forest trees still living in the south-east of England. Some of our common wild-flowers and water-plants had now made their appearance, such as the buttercup, marsh-

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[1] Gaudin, 'Feuilles fossiles de la Toscane'; Gaudin and Strozzi, 'Contributions à la Flore fossile italienne'; Lyell, 'Student's Elements,' 4th edit. p. 172.

[2] "Recherches sur les Végétaux fossiles de Meximieux," *Archiv. Mus. Lyon*, i. (1875-76) and his 'Monde des Plantes,' p. 314.

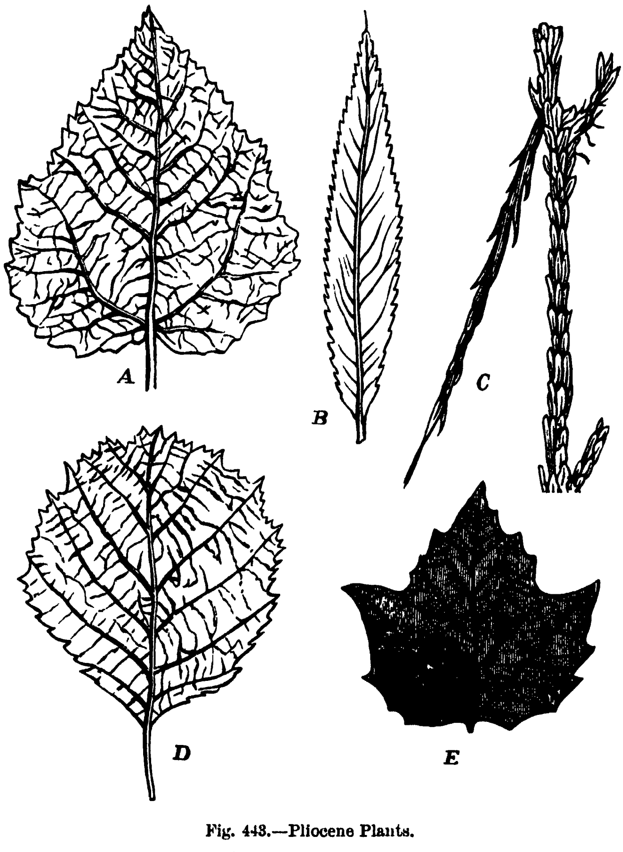

Fig. 443.—Pliocene Plants.

(A) Populus canescens; (B) Salix alba; (C) Glyptostrobus europæus; (D) Alnus glutinosa; (E) Platanus aceroides (½).

marigold, chickweed, milfoil, marestail, dock, sorrel, pondweed, sedge, cotton-grass, reed and royal fern.[1]

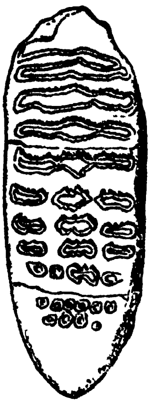

Fig. 444.—Elephas meridionalis, Nesti. Crown of molar (¼).

The fauna of the Pliocene period still retained a number of the now extinct types of earlier time, such as the *Deinotherium* and *Mastodon*. It was specially characterised also by troops of rhinoceroses, hippopotamuses, and elephants, the *Elephas meridionalis* being a distinctive form; by large herds of herbivora, including numerous forms of gazelle, antelope, deer, now mostly extinct, and types intermediate between still living genera. Among these were some colossal ruminants, including a species of giraffe and the extinct giraffe-like genera *Helladotherium* and *Samotherium*, as well as other types met with among the Siwalik beds of India (*Sivatherium*, Fig. 453, *Bramatherium*). The Equidæ were represented by the existing *Equus*, and by extinct forms, one of the most abundant of which was *Hipparion* (Fig. 445), like a small ass or quagga, with three toes on each foot, only the central one actually reaching the ground. Besides these animals there lived also various apes (*Mesopithecus*, Fig. 446, *Dolichopithecus*), likewise species of ox, cat, bear, machairodus, hyæna, fox, viverra, porcupine, beaver, hare, and mouse.

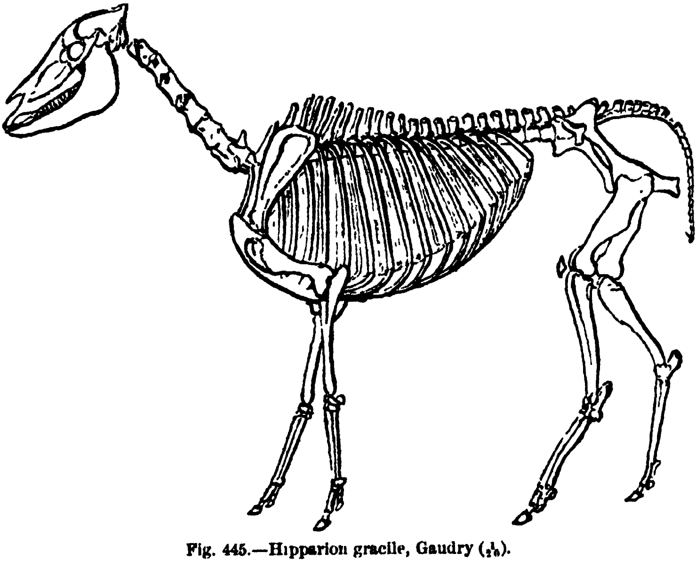

Fig. 445.—Hipparion gracile, Gaudry ($\frac{1}{16}$).

The advent of a colder period is well shown in the younger Pliocene deposits of south-eastern England, where a number of northern mollusks make their appearance. The proportion of northern species increases rapidly in the next succeeding or Pleistocene beds. The Pliocene period, therefore, embraces the long interval between the warm temperate climate of the later ages of Miocene and the cold Pleistocene time. The evidence of change of climate derivable from the English Pliocene marine mollusca may be grouped as in the subjoined table, which shows the gradual extirpation of southern and advent of northern forms in the long interval between the deposition of the oldest and newest Pliocene deposits.[1]

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[1] C. Reid, 'Pliocene Deposits of Britain,' *Mem. Geol. Surv.* (1890) pp. 185, 231.

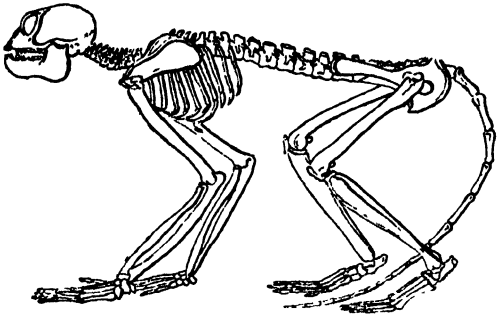

Fig. 446.—Mesopithecus Pentelici, Gaudry (1/8)

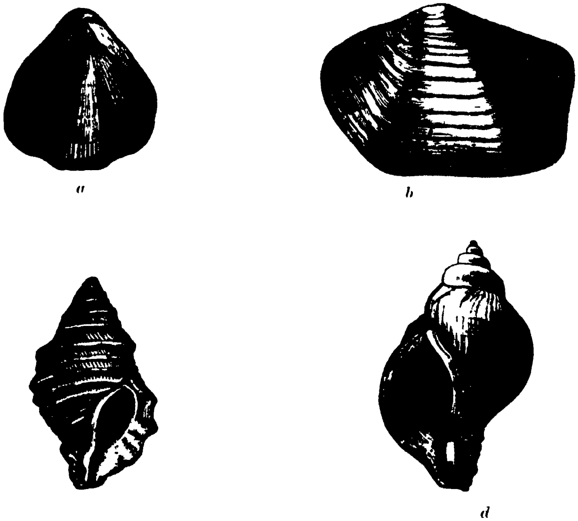

Fig. 447.—Pliocene Marine Shells.

a, Rhynchonella psittacea; *b*, Panopæa norvegica (1/2); *c*, Purpura lapillus (1/2), *d*, Trophon antiquus (1/2). All these species still live in the seas around Britain.

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[1] C. Reid, *op. cit.* p. 145.

	Total Species.	Arctic.	Mediterranean.	Extinct.
Weybourn Crag . . .	53	9	0	5
Chillesford Crag . . .	90	7	2	14
Fluvio-marine Crag . .	112	9	7	18
Red Crag of Boyton, &c. .	119	13	23	55
Red Crag of Walton . .	148	2	22	50
Coralline Crag . . .	420	1(?)	75	169

§ 2. Local Development.

Britain.[1]—In the Pliocene period, after a long period of exposure as a land-surface, during which a continuous and ultimately stupendous subaerial denudation was in progress, Britain underwent a gentle, but apparently only local, subsidence. We have no evidence of the extent of this depression. All that can be affirmed is that the south-eastern counties of England began to subside, and on the submerged surface some sand-banks and shelly deposits were laid down, very much as similar accumulations now take place on the bottom of the North Sea. These formations, termed generally "Crag," are followed by estuarine and fresh-water strata, the whole being subdivided, according to the proportion of living species of shells, into the following groups in descending order :—

Base of the Pleistocene.	Arctic Fresh-water Bed (with *Salix polaris*, *Betula nana*, &c.)	
Newer Pliocene (cold temperate).	*Leda myalis* Bed, classed provisionally as Pliocene.	
	Forest-bed group (10 to 60 feet). Upper Fresh-water, Estuarine, Lower Fresh-water.	Gravels with *Elephas meridionalis* at Dewlish.
	Weybourn Crag (and Chillesford Clay ?), 1 to 22 feet.	
	Chillesford Crag (5 to 15 feet).	
	Norwich Crag and *Scrobicularia* Crag (5 to 10 feet).	147 feet at Southwold.
	Red Crag of Butley, &c.	
	Walton Crag (Lower Red Crag, 25 feet).	
Older Pliocene (warm temperate).	St. Erth Beds.	
	Coralline Crag (40 to 60 feet).	
	Lenham Beds (Diestian).	
	Box-stones and phosphate beds (with derivative early Pliocene fossils).	

OLDER PLIOCENE.—The deposits of this age probably at one time extended over a large part of the south and south-east of England, but they have been reduced by denudation to a few widely separated patches, the largest of which, around Oxford in Suffolk, does not cover more than about ten square miles. They consist chiefly of shelly sands known as the Coralline Crag of Suffolk, but a small outlier of fossiliferous sand occurs on the edge of the North Downs at Lenham, and other ironstone patches, probably of the same age, cap the Down as far as Folkestone. Far to the west, at St. Erth in Cornwall, an isolated deposit of older Pliocene age has been detected. These thin and scattered fragments convey no adequate conception of the length or importance of the geological period which they represent. It is not until we pass into the north of Italy and the basin of the Mediterranean that we discover the Pliocene system to be represented by thick accumulations of upraised marine strata comparable in extent and thickness to some of the antecedent Tertiary series.

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[1] Prestwich, *Q. J. Geol. Soc.* xxvii. ; Lyell, 'Antiquity of Man,' chap. xii. ; Searles Wood, "Crag Mollusca," *Palæont. Soc.* ; H. B. Woodward, "Geology of Norwich," and W. Whitaker, "Geology of Ipswich, &c.," both in *Mem. Geol. Survey.* The fullest account of the subject will be found in the monograph by C. Reid, already cited, on the 'Pliocene Deposits of Britain,' *Mem. Geol. Survey*, 1890.

A strongly marked break, both stratigraphical and palæontological, separates the Pliocene deposits of Britain from all older formations. They lie unconformably on everything older than themselves, and in their fossils show a great contrast even to those of the Oligocene series. The sub-tropical plants and animals of older Tertiary time are there replaced by others of more temperate types, though still pointing to a climate rather warmer than that of southern England at the present time.

A conglomeratic deposit (Nodule beds) forms the base of the Red Crag, and appears generally to underlie also the Coralline Crag. It includes fragments of various rocks such as flints, septaria, sandstones, quartz, quartzite, granite, and other igneous materials, together with a miscellaneous assortment of derivative fossils, including Jurassic ammonites and brachiopods, sharks' teeth and other fossils from the London Clay, the teeth of many land mammals (pig, rhinoceros, mastodon, tapir, deer, hipparion, &c.), and pieces of the rib-bones of whales. Many of these organic remains must have been derived from some older Pliocene deposit which has otherwise entirely disappeared. They have been to a large extent phosphatised, and hence have been extracted as a source of phosphate of lime. Among the contents of the deposit some of the most interesting and important are rounded pieces of brown sandstone, known as "box-stones," evidently derived from the denudation of a single horizon, and enclosing casts of marine shells. The general facies of the assemblage of shells obtained from these fragments of a lost formation points unmistakably to early Pliocene time. At present 16 species have been determined, all of which are well-known British Pliocene forms, except two which occur in Continental Pliocene deposits.[1]

Coralline Crag (Bryozoan, White, or Suffolk Crag) consists essentially of calcareous sands, mainly made up of shells and bryozoa, and is exposed at various localities in the county of Suffolk. According to the census of Searles Wood, published in 1882, the number of mollusks found in this deposit amounts to 420 species, of which 251 or 60 per cent are still living. Some of the genera of shells give a southern character to the fauna, such as large and showy species of *Voluta*, *Cassidaria*, *Cassis*, *Ficula*, *Hinnites*, *Chama*, *Cardita*, and *Pholadomya*, likewise *Ovula*, *Mitra*, *Triton*, *Vermetus*, *Ringicula*, *Verticordia*, *Coralliophaga*, and *Solecurtus*. Characteristic species are *Cardita corbis*, *Cardita senilis*, *Limopsis pygmæa*, *Ringicula buccinea*, *Voluta Lamberti* (Fig. 450), *Pyrula reticulata*, *Astarte Omalii* (Fig. 449), *Pholadomya histerna*, *Pecten opercularis*, *Lingula Dumortieri*, and *Terebratula grandis*. Hardly less abundant and varied are the bryozoa or "Corallines," from which the name of the deposit is taken. No fewer than 118 species have been named, of which 76, or about 64 per cent, appear to be extinct. Specially characteristic and peculiar are the large massive forms known as *Alveolaria* and *Fascicularia* (Fig. 448). There are three species of corals all extinct. Of the 16 species of echinoderms at present known, only three are now living. Remains of fishes are of common occurrence, especially in the form of gadoid otoliths. Teeth and dermal spines of the skate and wolf-fish are met with, and to these shell-eating fish the broken condition of so many of the shells may probably be ascribed. Traces of one of the larger dolphins have been found, but no remains of any of the contemporaneous land-mammals, though a few drifted land-shells show that the land lay probably at no great distance. The Coralline Crag may be regarded as an elevated shell-bank, which accumulated on the floor of a warm sea at a depth of from 40 to 60 fathoms.[2]

Lenham Beds, Diestian.—On the edge of the Chalk Down of Kent near Lenham, patches of sand are found capping the Chalk, and descending into pipes on its surface, at a height of more than 600 feet above the sea, and other similar nests of ferruginous sands are met with along the downs as far as Folkestone. At first these deposits were thought to be portions of the base of the Tertiary series, but the occurrence of apparently Pliocene shells in them led to a more thorough investigation of them, with the result that they have been proved to be of the same age as similar deposits which cap the hills on the other side of the Straits of Dover from Boulogne into Belgian Flanders, whence they stretch northwards as a wide continuous sheet into Holland. These sands, known as Diestian, have yielded at Diest and Antwerp a large assemblage of fossils, which prove them to be of older Pliocene age. Of the Diestian fossils of Holland and Belgium so large a proportion has been detected, generally in the form of hollow casts, in the Lenham deposits as to leave no doubt of the geological horizon of these scattered fragments of a formation. About 67 species have been obtained from Lenham, the southern character of which is indicated by the genera *Ficula* (*Pyrula*), *Xenophora* (*Phorus*), *Triton*, and *Avicula*, with abundant examples of *Arca diluvii*, *Cardium papillosum*, and *Cupularia canariensis*. It is interesting to notice the great change of level which this fragmentary formation serves to prove since older Pliocene time in the south of England. From the general character of the fauna found at Lenham it is probable that the shells lived in a depth of not less than 40 fathoms of water. This vertical amount, added to the present height of the deposit above the sea, gives a minimum of 860 feet of uplift.[1]

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[1] C. Reid, *op. cit.* p. 6 *seq.*

[2] C. Reid, *op. cit.* p. 19 *seq.*

Fig. 448.—Pliocene Polyzoon. Fascicularia aurantium, M. Edw. (½).

St. Erth Beds.—The only other fragment yet known of older Pliocene formations in Britain lies far to the west between St. Ives and Mount's Bay in Cornwall, where a patch of clay, probably less than a quarter of a square mile in area, contained in a hollow of the slates, has preserved an interesting series of organic remains. Among the forms which connect this deposit with corresponding strata elsewhere the following may be mentioned: *Chemnitzia plicatula*, *Columbella sulcata*, *Cypræa avellana*, *Eulimene terebellata*, *Fissurella costaria*, *Lacuna suboperta*, *Melampus pyramidalis*, *Nassa reticosa*, *Natica millepunctata*, *Ringicula acuta*, *Trochus noduliferens*, *Turritella incrassata*, *Cardita aculeata*, *Cardium papillosum*.[2]

NEWER PLIOCENE.—The British deposits of this age are, so far as we know, confined to the counties of Norfolk and Suffolk. They are separated by a considerable break from the older series, for they lie on an eroded surface of the latter, and pass across it so as to rest upon the Eocene formations, and even on the Chalk. There is likewise a marked contrast between the fauna of the two series. The newer deposits show that the break must represent a long period of geological time, during which a great change of climate took place in Europe, for the southern forms are now found to have generally disappeared, and to have been replaced by northern forms that, following the change of temperature, had migrated from the colder north.

Red Crag.—Under this name is classed a series of local accumulations of dark-red or brown ferruginous shelly sand, which, though well marked off from the Coralline Crag below, is less definitely separable from the Norwich Crag above. Judging from the variations in its fossil contents, geologists have inferred that some portions of the deposit are older than others, and that they successively overlap each other as they are followed northward. The oldest part is believed to occur at the southern end of the area at Walton, where it yields a fauna closely similar to that of the Coralline Crag. This portion is lost a few miles farther north, where the Red Crag of Butley appears, containing many Arctic mollusca. In the older crag of Walton the advent of a colder climate is indicated by the appearance of the northern shells *Buccinum glaciale* and *Trophon scalari-*

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[1] C. Reid, *op. cit.* pp. 42, 69.

[2] *Ibid.* pp. 59, 236.

formis, but many of the southern forms still linger, such as *Cerithium trilineatum*, *Chemnitzia internodula*, *Nassa limata*, *Natica millepunctata*, *Ovula spelta*, *Pleurotoma hystrix*, *Turritella incrassata*, *Cardita corbis*, *Cytherea rudis*, and *Limopsis pygmæa*. In the younger part of the Red Crag the proportion of northern shells greatly increases. Among them are *Cancellaria viridula*, *Natica occlusa*, *Pleurotoma pyramidalis*, *P. scalaris*, *Trophon scalariformis*, *T. Sarsii*, *Cardium grœnlandicum*, *Leda lanceolata*, and *Solen gladiolus*. Characteristic shells of the Red Crag are *Actæon Noæ*, *Capulus obliquus*, *Cerithium tricinctum*, *Eulimene terebellata*, *Natica hemiclausa*, *Pleurotoma turrifera*, *Scalaria funiculus*, *Trochus cineroides*, *Astarte obliquata*, *Tellina Benedeni*, which are all extinct. A few land and fresh-water mollusks have been met with in the deposit, including *Ancylus lacustris*, *Helix hispida*, *Limnæa palustris*, *Paludina media*, *Planorbis complanatus*, *Pupa muscorum*, *Succinea putris*, and *Corbicula fluminalis*.

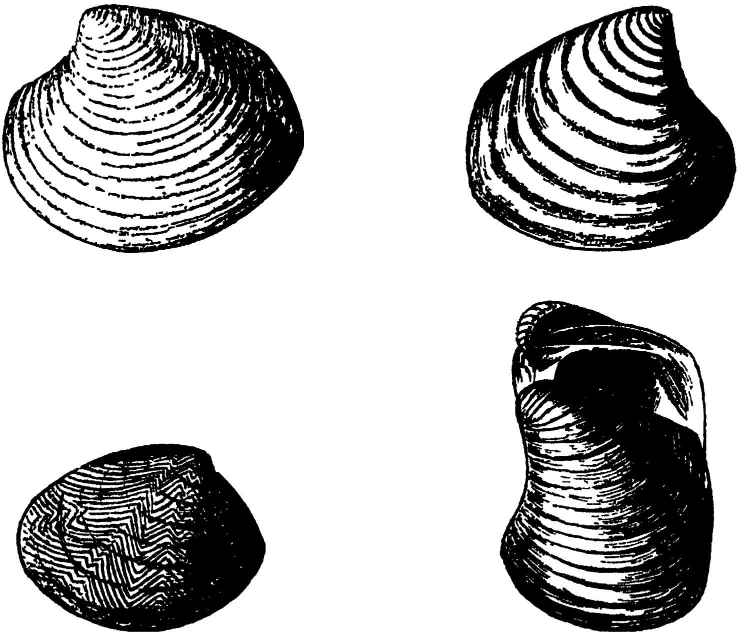

Fig. 449.—Pliocene Lamellibranchs

a, Astarte borealis Chemn. (living northern species); *b*, Astarte Omalii, Laj. (extinct); *c*, Nucula Cobboldiæ, Sow. (extinct). *d*, Congeria subglobosa, Partsch. (extinct) (⅔).

Norwich Crag (Fluvio-marine or Mammaliferous Crag).—As above stated, it is impossible to draw any sharp line between the Red and the Norwich Crags. They probably represent varying local conditions of sedimentation rather than different ages of deposit. The Norwich Crag consists of a few feet of shelly sand and gravel, containing, so far as known, 134 species of shells, of which 16 per cent are extinct. About 20 of the species are land or fresh-water shells. The name of "Mammaliferous" was given from the large number of bones, chiefly of extinct species of elephant, recovered from this deposit. The mammalian remains comprise both land and marine forms. Of the former are *Lutra Reevli*, *Gazella anglica*, *Cervus carnutorum*, *Equus Stenonis*, *Mastodon arvernensis*, *Elephas antiquus*, *Arvicola intermedius*, *Trogontherium Cuvieri*. The marine animals include *Trichechus Huxleyi* and *Delphinus delphis*. A few remains of sea-fishes have also been found, such as the cod and pollack. Among the mollusca the following are characteristic forms: *Paludina media*, *Hydrobia ventrosa*, *Turritella communis*, *Trophon scalariformis*, *Littorina littorea*, *Mytilus edulis*, *Nucula Cobboldiæ* (Fig. 449), *Cardium edule*. One interesting feature is the decided mixture of northern species of shells, such as *Rhynchonella psittacea*, *Scalaria grœnlandica* (Fig. 450), *Panopæa norvegica*, and *Astarte borealis* (Fig. 449). These, with those above mentioned, were forerunners of the great invasion of Arctic plants and animals which, in the beginning of the Quaternary ages, came southward into Europe, with the severe climate of the north.

The upper part of the Red Crag sometimes passes into a band, called from its prevailing mollusk the "Scrobicularia Crag." This band, which is probably a continuation of the Norwich Crag of Norfolk, is seen at Chillesford, in Suffolk, to pass upward without a break into the Chillesford Crag.[1]

Chillesford Crag.—Under this name is grouped a local series of sands with occasional seams of clay and bands of shells. Some of these shells (*Mya arenaria*) are upright and in the position in which they lived. Northern forms are still more prominent here, while a number of the common Red Crag forms seem to have disappeared. The fauna comprises *Buccinum undatum*, *Hydrobia subumbilicata*, *Melampus pyramidalis*, *Natica incrassata*, *N. reticosa*, *Purpura lapillus*, *Ringicula ventricosa*, *Trochus tumidus*, *Trophon antiquus*, *Anomia ephippium*, *Astarte borealis*, *Cardita corbis*, *Cardium grœnlandicum*, *Cyprina islandica*, *Leda lanceolata*, *Lucina borealis*, *Mactra arcuata*, *Nucula Cobboldiæ*, *Panopæa norvegica*, *Pecten opercularis*, *Tellina calcarea*, *Rhynchonella psittacea*.

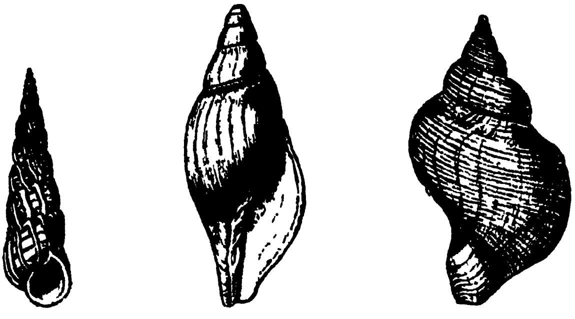

Fig. 450.—Pliocene Gasteropods.

a, Scalaria grœnlandica, Chemn., *b*, Voluta Lamberti, Sow. (½); *c*, Trophon antiquus, Mull. (Fusus contrarius) (½).

Weybourn Crag and Chillesford Clay.—At Chillesford the Chillesford Crag passes insensibly upwards into the Chillesford Clay, which is there a fine micaceous loam or clay containing a few shells and fish-vertebræ. Among the shells of this deposit are *Buccinum undatum*, *Purpura lapillus*, *Astarte compressa*, *Cyprina islandica*, *Lucina borealis*, *Nucula Cobboldiæ*, *N. tenuis*, *Tellina obliqua*, *Cardium grœnlandicum*. Traced northwards the Chillesford Clay appears to pass into the deposit known as the Weybourn Crag, which is a band of laminated green and blue clays with loamy sand full of marine shells, well seen along the Norfolk coast to the west of Cromer. This member of the series has yielded 53 species and marked varieties of marine shells (*Tellina balthica*, specially abundant, *Saxicava arctica, Nucula Cobboldiæ, Mya arenaria, M. truncata, Cyprina islandica, Astarte compressa, A. sulcata, A. borealis, Turritella terebra, Trophon antiquus, Purpura lapillus, Pleurotoma turricola, Littorina littorea, Buccinum undatum*, &c.), of which five, or 10·6 per cent, are extinct, and nine species are Arctic forms.

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[1] C. Reid, *op. cit.* p. 100. For an account of the vertebrate fauna of these deposits see E. T. Newton's monographs on "The Vertebrata of the Forest Bed Series of Norfolk and Suffolk" (1882) and "The Vertebrata of the Pliocene Deposits of Britain" in *Mem. Geol. Surv.*

Forest-bed Group.[1]—One of the most familiar members of the English Pliocene series is that to which the name of the "Cromer Forest-bed" has been given. It occurs beneath the cliffs of boulder-clay on the Norfolk coast, and was believed to mark a former land-surface, with the stumps of trees *in situ*. More careful study, however, has shown that the stumps have all been transported to their present position, and lie not on an old soil, but in an estuarine deposit. It is now agreed that the group of strata known as the Forest-bed series may be divided into three groups, an upper and lower fresh-water bed separated by an estuarine layer. The general character of the strata comprised in this member of the Pliocene series is shown in the subjoined table :—

	Leda myalis Bed (p. 1014).
Cromer Forest-bed Group.	Upper Fresh-water Bed, consisting of sand mixed with blue clay (2–7 feet) and enclosing twigs and shells (*Succinea putris, Cyclas cornea, Valvata piscinalis, Bythinia tentaculata, Pisidium amnicum*, &c.)
	Forest-bed (estuarine), composed of laminated clay and lignite, alternating gravels and sands with pebbles, cakes of peat, branches and stumps of trees, and mammalian bones, &c. (ranging up to more than 20 feet in thickness).
	Lower Fresh-water Bed, made up of carbonaceous, green, clayey silt full of seeds, with laminated lignite and loam.
	Weybourn Crag.

The vegetation preserved in this group of strata embraces at least 56 species of flowering plants, two of which, the water chestnut and spruce fir, do not appear to have belonged to the British flora since the Glacial period ; the others are nearly all still living in Norfolk. The variety of forest-trees points to a mild and moist climate ; they include the maple, sloe, hawthorn, cornel, elm, birch, alder, hornbeam, hazel, oak, beech, willow, yew, pine, and spruce. The land and fresh-water shells number 58 species, whereof five appear to be extinct (*Limax modioliformis, Nematura runtoniana, Paludina glacialis, P. media, Pisidium astartoides*) and five no longer live in Britain (including *Hydrobia Steinii, Valvata fluviatilis, Corbicula fluminalis*). The known marine shells in the Forest-bed series are so few in number (19 species) that they do not afford a satisfactory basis for comparison with other parts of the Pliocene formations. Some of them may have been washed out of the Weybourn Crag below, and they are all common Weybourn Crag fossils, including several extinct species (*Melampus pyramidalis, Tellina obliqua, Nucula Cobboldiæ*). They indicate that the climate of the time when they lived was probably not greatly different from that of the present day. Fourteen species of fishes have been recognised (*Platax Woodwardi*, cod, and tunny among marine forms, also perch, pike, barbel, tench, and sturgeon among fluviatile kinds). The fauna also includes two reptiles (*Tropidonotus natrix, Pelias berus*), four amphibians (frogs and tritons), five birds (eagle-owl, cormorant, wild goose, wild duck, shoveller duck), and fifty-nine mammals. These last-named fossils give the Forest-bed its chief geological interest. They include a few marine forms—seals, whales, walrus, and a large and varied assemblage of terrestrial and river-haunting forms, such as carnivores—*Machairodus*, *Canis lupus*, *C. vulpes*, *Hyæna crocuta*, *Ursus spelæus*, *Mustela martes*, *Gulo luscus*, *Lutra vulgaris*; ungulates—*Bison bonasus*, *Ovibos moschatus*, *Alces latifrons*, *Cervus elaphus* (and nine other species), *Hippopotamus amphibius*, *Sus scrofa*, *Equus caballus*, *E. Stenonis*, *Rhinoceros etruscus*, *Elephas antiquus*, *E. meridionalis*; rodents—*Arvicola arvalis*, *Mus sylvaticus*, *Castor fiber*, *Trogontherium Cuvieri*; insectivores—*Talpa europæa*, *Sorex vulgaris*, *S. pygmæus*, *Myogale moschata*. The contrast between this strange collection of animals and the familiar aspect of the plants associated with them was long ago remarked by Lyell.[1] The most abundant and conspicuous forms are the three species of elephant, while the hippopotamus and rhinoceros are of common occurrence. Of the two horses one is extinct, the bison and wild boar have survived, while the whole of the remarkably numerous species of deer have disappeared, with the single exception of the red-deer. The carnivores embraced also living and extinct forms, for the long-vanished machairodus haunted the same region with our still surviving fox, otter, and marten, and with other animals which, like the hyæna, wolf, and glutton, though no longer found in Britain, survive elsewhere. The total species of land mammals (exclusive of bats) found in the Forest-bed is 45, while the corresponding series of the living British fauna numbers only 29 species. Of the 30 large land mammals found in the Forest-bed only three are now living in Britain, or have died out there within the historic period, and only six species have survived in any part of the world.[2]

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[1] On this group see Lyell, *Phil. Mag.* 3rd ser. xvi. (1840) p. 245, and his 'Antiquity of Man' ; Prestwich, *Quart. Journ. Geol. Soc.* xxvii. (1871) pp. 325, 452 ; *Geologist*, iv. (1861) p. 68 ; John Gunn, 'Geology of Norfolk,' 1864 ; C. Reid, *Geol. Mag.* (2) vol. iv. (1877) p. 300 ; vii. (1880) p. 548 ; 'Geology of the Country around Cromer' in *Mem. Geol. Surv.* 1882 ; 'Pliocene Deposits of Britain' in *Mem. Geol. Surv.* 1890 ; E. T. Newton's monographs cited on the previous page.

The Cromer Forest-bed is succeeded on the Norfolk coast by some sands and gravels of which the true position in the series of formations has not yet been definitely fixed. They include two distinct members, though their precise relations to the Crag below and the glacial materials above are still not satisfactorily settled. The lower band is known as the *Leda myalis* bed, and the upper as the Arctic fresh-water bed. The former may be provisionally placed with the rest of the Pliocene formations of Norfolk. The latter can hardly be separated from it, and would not be so separated but for the remarkable character of its few included fossils. These indicate such a great increase of cold as to show that the conditions of the Glacial period must now have set in. Hence the Arctic fresh-water bed is classed with the Pleistocene series.

Leda myalis Bed.—This band, nowhere more than 20 feet in thickness, consists of false-bedded loamy sand, loam or clay, and a little gravel, and lies sometimes on the Forest-bed, sometimes on the Weybourn Crag. This unconformability may mark a considerable interval of time. Among the scanty organisms of this deposit the following may be mentioned: *Buccinum undatum*, *Littorina littorea*, *L. rudis*, *Purpura lapillus*, *Trophon antiquus*, *Astarte borealis*, *Cardium edule*, *Cyprina islandica*, *Leda myalis*, *Mya truncata*, *Mytilus edulis*, *Ostrea edulis*, *Tellina balthica*. Some of these shells (the *Astarte*, *Leda*, and *Mya*) are found with the valves united in the position of life. The *Leda* is an Arctic species not known in any of the underlying formations.

Arctic Fresh-water Bed.—Reference may be made here to this deposit which is so intimately linked with that last described. It consists of stiff blue loam, clay, and sand, sometimes more than two feet thick, like the deposits of transient floods. Its plants include a number of mosses, with the dwarf Arctic birch and willow (*Betula nana* and *Salix polaris*, Fig. 454)—a vegetation wherein trees seem to have as completely disappeared as in the Arctic lands. It may indicate a lowering of temperature by about 20 Fahr.—"a difference as great as between the south of England and the North Cape at the present day, and sufficient to allow the seas to be blocked with ice during the winter, and to allow glaciers to form in the hilly districts."[3] Among the plants a few land-shells have been found such as *Succinea putris*, *S. oblonga*, *Pupa muscorum*, together with some wing-cases of beetles.

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[1] 'Antiquity of Man,' 1st edit. (1863) p. 216. See also C. Reid, 'Pliocene Deposits of Britain,' p. 182.

[2] C. Reid, *op. cit.*

[3] C. Reid, *op. cit.* p. 198.

Various pebble-gravels occur in different parts of southern England, the true stratigraphical position of which is still undetermined. They are generally unfossiliferous. Some parts of them may be Pliocene. In the south-west, at Dewlish in Dorset, a deposit of sand and gravel has yielded a number of elephant bones and teeth referred to *Elephas meridionalis*, and pointing to an Upper Pliocene age.

Belgium and Holland.—The sea in which the English Pliocene deposits were laid down probably extended across Belgium, Holland, and the extreme north of France, but no trace of its presence has yet been found eastwards in Germany. In Belgium the base of the Pliocene is found to rest with a strong unconformability on all older deposits, even on the Miocene sands (Bolderian and Anversian). The older Pliocene group consists chiefly of sand, and has been named Diestian from the locality where it is typically developed. At Antwerp, Utrecht, and other places it has yielded a large assemblage of fossils (190 species), all of which save 22 occur in the English Coralline Crag and Lenham beds. This horizon may be paralleled with the Plaisancian group of southern France and Italy. Above the Diestian sands comes the group known as Scaldesian, which is likewise made up mainly of sands enclosing a fauna closely resembling that of the lower part of the English Red Crag (Walton Crag). The higher groups seen in England have not yet been identified by means of fossils in Belgium and Holland. Yet the Pliocene deposits attain in these countries a far greater thickness than they do in England. At Amsterdam, for example, a deep boring has passed through younger Tertiary strata to a depth of 1096 feet below sea-level, and yet it is doubtful, according to Mr. Reid, whether any portion of this great thickness is so old as the Diestian group.[1] Belgian Pliocene deposits, of which the precise horizons have not been determined, have yielded a large number of bones of marine mammalia, including seals, dolphins, and numerous cetaceans, as well as remains of fishes (*Carcharodon*, *Lamna*, *Oxyrhina*, &c.)

France.—In the north of this country unfossiliferous sands which cap the hills between Boulogne and Calais at heights of 400 or 500 feet, and stretch eastwards into French Flanders, are believed to be continuations of the Lenham and Diestian group.[2] In central France younger Pliocene deposits associated with the volcanic materials of that region have preserved an interesting record of the terrestrial fauna of the time. The trachytic conglomerate of Perrier and the ossiferous deposits of other localities in Auvergne have yielded an abundant fauna, in which the apes are absent, the antelopes have dwindled in size and number, the deer have grown very abundant, true elephants for the first time appear, associated with a species of hippopotamus, nearly if not quite identical with the living African one, two kinds of hyæna, and the hipparion and machairodus that had survived from earlier times. This fauna indicates a decided change of climate to a more temperate character. Among the volcanic products of Haute Loire remains of *Mastodon arvernensis*, *Rhinoceros leptorhinus*, *Equus Stenonis*, and *Machairodus pliocænus* have been collected.

Along the southern coast of France, marine Pliocene deposits lying unconformably on every series older than themselves bear witness to the elevation of that region since Pliocene time, some of the beds reaching a height of 1150 feet above the present sea-level. These marine strata extend for some distance up the valley of the Rhone, where they mark the final deposits of the sea in that part of the mainland of Europe. They cap the plateaux and rise towards the north and west, indicating a maximum of elevation in that direction. The marls of Hauterives (formerly regarded as Miocene) are remarkable for their beds of coarse conglomerate, which represent some of the torrential deposits swept down from the neighbouring hills. These marls contain land and fresh-water shells.

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[1] *Op. cit.*, p. 220.

[2] C. Reid, *op. cit.* p. 50.

The whole series of Pliocene deposits in southern France has been divided into the following groups.[1]

Arnusian.	Fresh-water and volcanic groups of Auvergne, &c. (St. Prest, Perrier[2]), with *Elephas meridionalis* in the younger and *Mastodon arvernensis* in the older deposits.
Astian.	Sands and clays of fluviatile or lacustrine origin, with a few shells (*Unio, Anodonta, Planorbis, Helix*) and a large and varied assemblage of terrestrial and fluviatile vertebrates (*Dolichopithecus, Machairodus, Caracal, Hyæna, Mastodon arvernensis, Rhinoceros leptorhinus, Tapirus arvernensis, Hipparion, Helarctos, Gazella, Cervus*, &c., Montpellier, Rousillon). Yellow sands with *Potamides Basteroti, Cerithium vulgatum, Congeria, Ostrea cucullata, Pecten benedictus, Cardium, Venus multilamella.*
Plaisancian (200-250 metres).	Sandy blue micaceous clays (with a large marine fauna (233 species) comprising *Nassa semistriata, Mitra striatula, Conus pelagicus, Cerithium vulgatum, Cytherea chione, Pecten benedictus, P. scabrellus, Ostrea cucullata*). Lower conglomerates sometimes 80 feet thick.

Italy.—As the Pliocene series is traced eastwards into Italy its lacustrine intercalations disappear and it becomes mainly a marine formation, which is so amply developed there that it might be taken as typical for the rest of Europe. Along both sides of the chain of the Apennines it forms a range of low hills, and has been named from that circumstance the "sub-Apennine series." In the Ligurian region, according to C. Mayer, it consists of the following groups in ascending order: 1, Messinian (= Zanclean of Seguenza), composed of (*a*) marls, conglomerates, and molasse (65 feet), with *Cerithium pictum, C. rubiginosum, Venus multilamella, Pecten cristatus, Turritella communis, T. subangulata*; (*b*) gypsiferous marls, limestones, dolomites (320 feet), traceable along the range of the Apennines as far as Girgenti in Sicily by its well-known gypsum zone, and containing *Turritella subangulata, Natica helicina, Pleurotoma dimidiata*, &c.; (*c*) gravels and yellow marls, with beds of lignite (upwards of 300 feet). 2, Astian, composed, at the foot of the Ligurian Apennines, of two groups, (*a*) blue marls with *Dentalium sexangulare, Turritella communis, T. tornata, Murex trunculus, Natica millepunctata*, &c.; (*b*) yellow sands with few fossils (300 feet and more).[3] More recently Professor Sacco has estimated the whole series in the central portion of the northern Apennines to have a thickness of nearly 1500 feet, which he groups as in the subjoined table:[4]—

Villafranchian (100 metres).	Fluvio-lacustrine alluvial sands, marls, clays, and conglomerates, with shells indicating a warm, moist climate, *Rhinoceros etruscus, Mastodon arvernensis*, &c.
Astian (100 metres).	Yellow sands and gravels, rich in littoral, marine or estuarine fossils.
Plaisancian (150 metres).	Marls and sandy clays with abundant marine fossils, from one-third to one-half of the shells belonging to living species.

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[1] Fontannes, 'Études Stratigraph. Paléont. pour servir à l'histoire de la Période, Tertiaire dans le Bassin du Rhône,' Paris, 1875-89; Depéret, *Ann. Sci. Géol.* xvii. (1885); *Mem. Soc. Géol. France*, I. fascic. 1. (1890).

[2] Potier, *Bull. Soc. Géol. France*, vii. (1879) p. 937.

[3] C. Mayer, *Bull. Soc. Géol. France* (3), v. 292.

[4] F. Sacco, 'Il Bacino Terziario del Piemonte,' Milan, 1889. See also De Stefani, *Atti. Soc. Tosc. Sci. Nat.* 1876-84.

Messinian (100 metres).	Sandy and clayey marls with seams of gypsum and limestone marking alternations of brackish-water and marine conditions. The shells include *Dreissena*, *Adacna*, *Cyrena*, *Neritodonta*, *Melania*, *Melanopsis*, *Hydrobia*, &c. Some of the marls are full of leaves (*Thuja*, *Phragmites*, *Myrica*, *Quercus*, *Castanea*, *Fagus*, *Ulmus*, *Ficus*, *Liquidambar*, *Laurus*, *Sassafras*, *Cinnamomum*, *Rhamnus*, &c.)

In Sicily a similar threefold grouping has been made by Seguenza, who has traced the same arrangement throughout a large part of the mainland. The lowest group is named by him Zanclean, and consists of marls and light-coloured limestones. The Plaisancian follows in a group of blue clays or marls, while the succeeding Astian consists of yellow sands. Of these stages the first is characterised by a fauna of which nearly $\frac{9}{10}$ are peculiar species, and only 85 out of 504 species, or about 17 per cent, belong to living forms which are nearly all found in the Mediterranean. Some of the common species of the deposit are *Janira flabelliformis*, *Terebratulina caput-serpentis*, *Rhynchonella bipartita*, *Dentalium triquetrum*, *Limopsis aurita*, *Leda dilatata*, *L. striata*, Phill., *Modiola phaseolina*. Tropical genera are well represented among the shells of the Italian Pliocene beds, while some of the still living Mediterranean genera occur there more abundantly, or in larger forms than on the present sea-bottom. The newer Pliocene deposits attain in Sicily a thickness of 2000 feet or more, rising to a height of nearly 4000 feet above the present sea-level, and covering nearly half of the island. To this series, though possibly it should be regarded as Pleistocene, is assigned a yellowish limestone, sometimes remarkably massive and compact, and 700 or 800 feet thick, yet full of living species of Mediterranean shells, some of which even retain their colour, and a part of their animal matter. It was during the accumulation of the Pliocene strata that the history of Etna began, the first stages being submarine eruptions, which were followed by the piling-up of the present vast sub-aerial cone upon the upraised Pliocene sea-bottom.

There is distinct evidence of a lowering of the climate of southern Europe during the deposition of the Italian Pliocene series. Not only did many of the distinctively southern types of shells gradually disappear from the Mediterranean, but others of markedly northern character, such as species of *Astarte*, took their place. The Italian Pliocene deposits, while chiefly of marine origin, contain also among their higher members lacustrine or fluviatile strata, in which remains of the terrestrial flora and fauna have been preserved. In the upper part of the valley of the Arno an accumulation of lacustrine beds attains a depth of 750 feet. The older portion consists of blue clays and lignites, with the abundant vegetation above referred to (p. 1004). The upper 200 feet consist of sands and a conglomerate ("sansino"), and have yielded remains of 39 species of mammals including *Macacus florentinus*, *Mastodon arvernensis*, *Elephas meridionalis*, *Rhinoceros etruscus*, *Hippopotamus amphibius* (*major*), *Hyæna* (3 sp.), *Felis* (3 sp.), *Ursus etruscus*, *Machairodus* (3 sp.), *Equus Stenonis*, *Bos etruscus*, *Cervus* (5 sp.), *Palæoryx*, *Palæoreas*, *Castor*, *Hystrix*, *Lepus arvicola*.[1] These strata are sometimes grouped as a higher zone of the Pliocene series under the name of Arnusian.[2]

Germany.—The absence of marine Pliocene formations in Germany has been already referred to. Among the lacustrine and fluviatile deposits of the period, however, numerous remains of the terrestrial flora and fauna have been preserved. One of the most celebrated localities for the discovery of these remains lies in the Mainz basin, where at Eppelsheim, near Worms, above the Miocene beds, described on p. 999, a group of sands and gravels with lignite (Knochensand), from 20 to 30 feet thick, has yielded a considerable number of mammalian bones. Among these the *Deinotherium giganteum* occurs, showing the long survival of this animal in central Europe; also *Mastodon angustidens*, *Rhinoceros incisivus*, and other species, *Hippotherium gracile*, several species of *Sus*, five or more of *Cervus*, and some of *Felis*.

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[1] C. J. Forsyth Major, *Q. J. Geol. Soc.* xli. (1885) p. 1.

[2] Mr. C. Reid suggests that the lignite deposits of the Val d'Arno (with *Tapirus*) may be much older than the rest of the lacustrine strata (with *Mastodon* and *Elephas*). A large proportion of the plants in them is extinct, and the tapir is the only animal whose remains are found in them. They may possibly be even Miocene.

Interesting collections of the terrestrial fauna of the period have been preserved in the calcareous tuffs of mineral springs in different parts of Germany. Besides numerous remains of land-plants, large numbers of land and fresh-water shells have been obtained from these deposits, which in some cases point to a colder climate than now exists. In the Franconian Alb, for instance, the occurrence of alpine and northern European forms of land-shells (*Patula solaria*, *Clausilia densestriata*, *C. filograna*, *Helix vicina*, *Pupa pagodula*, *Isthmia costulata*) has been noted. The mammals include many extinct as well as some still living forms (*Elephas antiquus*, *Rhinoceros Merkii*, *Sus scrofa*, *Cervus elaphus*, *C. capreolus*, *Bos primigenius*, *Equus caballus*, *Ursus spelæus*, *Meles vulgaris*, *Hyæna spelæa*).[1]

Vienna Basin.—In consecutive conformable order above the Miocene strata described on p. 1000, come the highest Tertiary beds of this area, referred to the Pliocene period, and known by the name of the "Congerian stage," from the abundance in them of the molluscan genus *Congeria* (*Dreissena*) (Fig. 449). They are separable into two tolerably well-defined zones, which in descending order are:—

2. Belvedere-Schotter—a coarse conglomerate or gravel of quartz and other pebbles, occasionally yielding bones of large mammals; Belvedere-sand—a yellow micaceous sand, forming the lower member of the zone and containing in its more compact portions abundant terrestrial leaves. These strata resemble part of the alluvia of a large river. Their name is taken from the Belvedere in Vienna, where they are well developed.
1. Inzersdorf Tegel—a tolerably pure clay reaching a depth of often more than 300 feet. This deposit, the youngest Tertiary layer that is widely distributed over the Vienna basin, points to continued and general submergence. The facies of its fossils, however, shows that the water no longer communicated freely with the open sea, but seems rather to have partaken of a Caspian character. Among the conspicuous mollusks are *Congeria subglobosa*, *C. Partschi*, *C. triangularis*, *C. spathulata*, *C. Czjzeki*, *Cardium carnuntinum*, *C. apertum*, *C. conjungens*, *Unio atavus*, *U. moravicus*, *Melanopsis martiniana*, *M. impressa*, *M. vindobonensis*, *M. Bouéi*. The mammals include *Mastodon longirostris*, *M. angustidens*, *Deinotherium giganteum*, *Aceratherium incisivum*, *Hippotherium gracile*, antelope, pig, *Machairodus cultridens*, *Hyæna hipparionum*. The flora includes, among other plants, conifers of the genera *Glyptostrobus*, *Sequoia*, and *Pinus*, also species of birch, alder, oak, beech, chestnut, hornbeam, liquidambar, plane, willow, poplar, laurel, cinnamon, buckthorn, with the Asiatic genus *Parrotia*, the Australian proteaceous *Hakea* (Fig. 442), and the extinct tamarind-like *Podogonium*.

In other parts of the Austro-Hungarian empire interesting evidence exists of the gradual uprise of the sea-floor during later Tertiary time and the isolation of detached areas of sea, so that the south-east of Europe must then have presented some resemblance to the great Aralo-Caspian depression of the present time. The Congerian stage brings before us the picture of an isolated gulf gradually freshening, like the modern Caspian, by the inpouring of rivers; but on both sides of the Carpathian range there were bays nearly cut off from the main body of water, and exposed to so copious an evaporation without counterbalancing inflow that their salt was deposited over the bottom. Of the Transylvanian localities, on the south side of the mountains, the most remarkable is Parajd, where a mass of rock-salt has been accumulated, having a maximum of 7550 feet in length, 5576 feet in breadth, and 590 feet in depth, and estimated to contain upwards of 10,595 millions of cubic feet. On the northern flank of the Carpathian Mountains, near Cracow, lie the famous and extensive salt-works of Wieliczka, with their massive beds of pure and impure rock-salt, gypsum, and anhydrite, some of the strata being full of fossils characteristic of the upper zones of the Vienna basin.

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[1] F. von Sandberger, 'Land und Süsswasser Conchylien der Vorwelt,' 1875, p. 936; *Sitzb. Bayer. Akad.* xxiii. (1893) Heft 1; Hellmann, *Palæontographica*, suppl.

The south-east of Europe, during later Tertiary time, was the scene of abundant volcanic action, and the outpourings of trachyte, rhyolite, basalt, and tuff were specially abundant over the low districts to the south of the Carpathian chain.

Greece.—A remarkable series of mammalian remains brought to light from certain hard red clays, alternating with gravels at Pikermi, in Attica, has been carefully worked out by M. Gaudry.[1] The list includes a monkey (*Mesopithecus*) intermediate between the living *Semnopithecus* of Asia and the Macaques. The carnivores are represented by *Simocyon*, *Mustela*, *Promephitis*, *Ictitherium*,—a genus allied to the modern civet—*Hyænictis*, *Hyæna*, *Machairodus*, and several species of *Felis*; the rodents by *Hystrix*, allied to the common porcupine; the edentates by the gigantic *Ancylotherium*; the proboscideans by *Mastodon* and *Deinotherium*; the pachyderms by Rhinoceros (several species), *Aceratherium*, *Leptodon*, *Hipparion*, and a gigantic wild boar (*Sus erymanthius*); the ruminants by *Camelopardalis*, of the same size as the living giraffe, *Helladotherium*—a form between the giraffe and the antelopes, three species of true antelope—*Palæotragus*, an antelope-like animal, *Palæoryx*, somewhat like the living African gemsbok, and *Palæoreas*, allied to the African eland and the gazelles, *Gazella*, a true gazelle, *Dremotherium*, probably a hornless ruminant like the living chevrotains. A few remains of birds have also been met with, including a *Phasianus*, related to our pheasant, a *Gallus*, smaller than our common domestic fowl, a *Grus*, closely related to the living crane; also bones of a turtle and a saurian (*Varanus*). This fauna is remarkable for the extraordinary abundance of its ruminants, the colossal size of many of the forms, such as the giraffe and *Helladotherium*, the singular rarity of the smaller mammals, the marked African facies which runs through the whole series, and the number of transitional types which it contains. Out of the 31 genera of mammals which have been obtained, 22

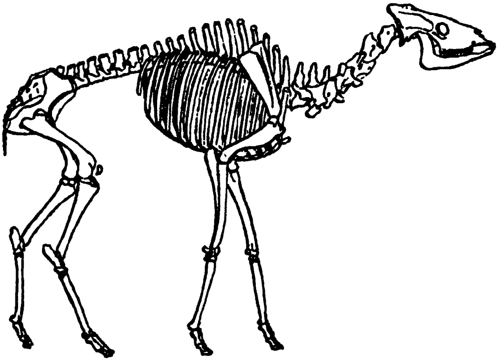

Fig. 451.—Helladotherium Duvernoyi, Gaudry ($\frac{1}{50}$).

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[1] 'Animaux fossiles et Géologie de l'Attique,' 4to, 1862, with volume of plates; *Bull. Soc. Géol. France*, xiv. (1885-86) p. 288. See also Roth and Wagner, *Abhandl. Bayer. Akad.* vii. (1854); T. Fuchs, *Denksch. Akad. Wien*, xxxvii. (1877) 2e Abtheil, p. 1; *Boll. Com. Geol. Ital.* ix. (1878) p. 110; W. T. Blanford, Address, *Geol. Sect. Brit. Assoc.* 1884. W. Dames (*Zeitsch. Deutsch. Geol. Ges.* xxxvi. 1883, p. 9) has added a species of *Cervus* and one of *Mus* to the previously known Pikermi forms.

are extinct. The Pikermi beds have been classed as Upper Miocene, but the occurrence of 4 characteristic marine Pliocene species of shells below them (*Pecten benedictus*, *Spondylus gæderopus*, *Ostrea lamellosa*, *O. undata*) justifies their being placed in a later stage of the Tertiary series. They are shown by Fuchs to form part of the Pliocene series of Attica, and lie in the highest part of that series.

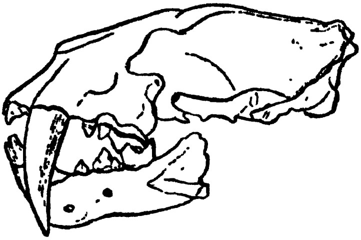

Fig. 452.—Head of Machairodus, the sabre-toothed Tiger, reduced.

Samos.—In an irregular deposit of gravels, sandstones, and marls in the island of Samos, Dr. Forsyth Major has discovered a large assemblage of vertebrate remains of an age similar to that of the Pikermi strata. Among the fossils obtained by him are many of the same species as are found at the Greek locality, such as *Promephitis Larteti*, *Mustela palæattica*, *Lycyæna Chæretis*, *Ictitherium robustum*, *I. hipparionum*, *Ancylotherium Pentelici*, *Mastodon Pentelici*, *Rhinoceros pachygnathus*, *Hipparion mediterraneum*, *Sus erymanthius*; seven antelopes, *Palæoreas Lindermayeri*, *Gazella brevicornis*, *Palæoryx Pallasii*, and two others. Besides these, there are some half-dozen antelopes of African types, and true edentates, *Orycteropus Gaudryi*, *Palæomanis Neas*, a new genus of gigantic ruminants, *Samotherium*, belonging to the family of the giraffes, and recalling the *Helladotherium* of Pikermi, and an ostrich (*Struthio Karatheodoris*).[1]

India.—Not less important than the massive Pliocene accumulations of the Mediterranean basin, are those which have been found in Sind, the Punjab, and other north-western tracts of India. In Sind, the noteworthy fact has been made out by the Indian Geological Survey that, from the Upper Cretaceous to the Pliocene beds, the whole succession of strata, with some trifling local exceptions, is conformable and continuous; yet contains evidence of alternations of marine and terrestrial conditions, the latest

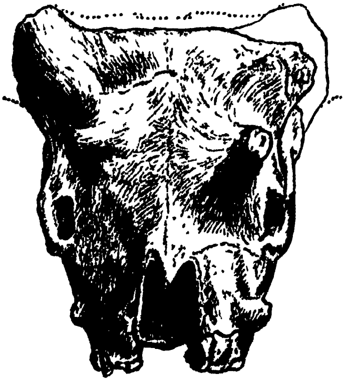

Fig. 453.—Sivatherium giganteum, Falc, reduced.
A gigantic form of antelope having two pairs of horns, found in the Siwalik beds of India.

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[1] *Compt. rend.* 31st Dec. 1888; 1891, pp. 608, 708.

marine intercalations being of Miocene date. The upper division of the Manchhar group (p. 1002) is not improbably referable to the Pliocene period. It consists of clays, sandstones, and conglomerate, 5000 feet thick, which have yielded some indeterminable fragmentary bones. Similar strata cover a vast area in the Punjab. They are admirably exposed in the long range of hills termed the Sub-Himalayas, which from the Brahmaputra to the Jhelum, a distance of 1500 miles, flank the main chain, and consist chiefly of soft massive sandstone, disposed in two parallel lines of ridge, having a steep southerly face and a more gentle northerly slope, and separated by a broad flat valley. These strata, with an aggregate thickness of between 12,000 and 15,000 feet, contain representatives of the older Tertiary or Nummulitic series, followed by younger Tertiary deposits which are classed together in what has been termed the Siwalik group. This group is of fresh-water origin, for its included organisms are entirely land or fresh-water forms. Its component clays, sandstones, and conglomerates have been deposited by great rivers, which appear to have flowed from the Himalayan chain by the same outlets as their modern representatives. These deposits vary according to their position relatively to the great rivers. They have been involved in the last colossal movements whereby the Himalayas have been upheaved, yet their structure shows that the same distribution of the watercourses has been maintained as existed before the disturbance. In this instance, as in that of the Green River through the Uinta range in western America, the inference seems to be legitimate that the elevation of the mountains must have proceeded so slowly that the erosion by the rivers kept pace with it, and the positions of the valleys were therefore not sensibly changed (see p. 1078).

The Siwalik fauna consists partly of a few land or fresh-water mollusks, some, if not all, of which are identical with living species; but chiefly of mammalia; and the following list comprises the vertebrate fauna so far as at present known:[1]—

MAMMALIA.—Primates.—*Palæopithecus*, 1 sp.; *Macacus*, 2; *Cynocephalus*, 2.
Carnivora.—*Mustela*, 1; *Mellivora*, 2; *Mellivorodon*, 1; *Lutra*, 3; *Hyænodon*, 1; *Ursus*, 1; *Hyænarctos*, 3; *Canis*, 1; *Amphicyon*, 1; *Viverra*, 2; *Hyæna*, 5; *Lepthyæna*, 1; *Æluropsis*, 1; *Ælurogale*, 1; *Felis*, 5; *Machairodus*, 2.
Proboscidea.—*Elephas*, 6 (*Euelephas*, 1; *Loxodon*, 1; *Stegodon*, 4); *Mastodon*, 7.
Ungulata.—*Chalicotherium*, 1; *Rhinoceros*, 3; *Equus*, 2; *Hipparion*, 2; *Hippopotamus*, 2; *Tetraconodon*, 1; *Sus*, 7; *Hippohyus*, 2; *Sanitherium*, 1; *Merycopotamus*, 3; *Cervus*, 4; *Dorcatherium*, 2; *Tragulus*, 1; *Palæomeryx*, 1; *Bramatherium*, 1; *Helladotherium* (?), 1; *Hydaspitherium*, 2; *Sivatherium*, 1; *Vishnutherium*, 1; *Giraffa*, 1; *Alcelaphus*, 1; *Gazella*, 1; *Oreas* (?), 1; *Palæoryx* (?), 1; *Leptobos*, 2; *Bubalus*, 4; *Bison*, 1; *Bos*, 3; *Bucapra*, 1; *Capra*, 2; *Camelus*, 2; *Boselaphus*, *Hippotragus*, *Cobus*.
Rodentia.—*Rhyzomys*, 1; *Hystrix*, 1; *Lepus*, 1.
AVES.—*Phalacrocorax*, 1; *Leptoptilus*, 1; *Pelecanus*, 2; *Mergus*, 1; *Struthio*, 1.
REPTILIA.—Crocodilia.—*Crocodilus*, 2; *Gavialis*, 5; *Rhamphosuchus*, 1.
Lacertilia.—*Varanus*, 1.
Chelonia.—*Colossochelys*, 1; *Testudo*, 2; *Bellia*, 2; *Damonia*, 1; *Batagur*, 1; *Pangshura*, 1; *Emyda*, 4; *Trionyx*, 1; *Clemmys*, 7; *Chitra*, 1.
PISCES.—*Bagarius*, 1; *Arius*, 2; *Rita*, 1; *Chrysichthys*, 1; *Clarias* (?), 1; *Carcharodon*, *Carcharias*.

In this list there is considerable resemblance to the grouping of mammalia in the Pikermi deposits just referred to, particularly in the preponderance of large animals, the absence or rarity of the smaller forms (rodents, bats, insectivores), and the marked Miocene aspect of certain parts of the fauna. Mr. Blanford and his colleagues of the

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[1] Falconer and Cautley, 'Fauna Antiqua Sivalensis,' 1845-49. Medlicott and Blanford, 'Geology of India,' p. 577. Blanford, *Brit. Assoc.* 1880, p. 577; Address, *Geol. Sect. Brit. Assoc.* 1884. Lydekker, 'Palæontologia Indica,' ser. x. vols. i. ii. iii. *Records Geol. Surv. India*, 1883, p. 81; 'Cat. Sewalik Vert. Ind. Mus.' 1885-86, and Catalogues of British Museum.

Geological Survey of India have, however, shown that, though usually classed as Miocene, the Siwalik fauna has such relations to Pliocene and recent forms as are found in no true Miocene fauna. The large proportion of existing genera is the most striking feature of the assemblage. Twelve of the genera are known elsewhere, 7 are Miocene and Pliocene; of the still living genera 9 range back in Europe to Upper Miocene time, 10 only to Pliocene, while 6 are only known elsewhere as living forms or as occurring in post-Pliocene beds. The large preponderance of species belonging to such familiar genera as *Macacus*, *Ursus*, *Elephas*, *Equus*, *Hippopotamus*, *Bos*, *Hystrix*, *Mellivora*, *Meles*, *Capra*, *Camelus*, and *Rhizomys*, give the whole assemblage a singularly modern aspect. It should be added that, of the six or seven determinable reptiles, three are now living in northern India; that of the birds, one is probably identical with the living ostrich, and that all the known land and fresh-water shells, with one possible exception, are of existing species.[1]

North America.—It appears to be doubtful whether any of the Tertiary deposits of the Atlantic border can be referred to the Pliocene series. They seem to be rather older and to be covered directly by post-Pliocene and recent accumulations.[2] In the Upper Missouri region, the White River group (p. 1002) is overlain by other fresh-water beds, 300 to 400 feet thick (Loup River group of Meek and Hayden, or Niobrara group of Marsh), from which an interesting series of vertebrate remains has been obtained. Among these, are those of an eagle, a crane, and a cormorant; a tiger, larger than that of India, an elephant, a mastodon, several rhinoceroses, the oldest known camels (*Procamelus*, *Homocamelus*), equine animals of the genera *Protohippus*, *Pliohippus*, *Merychippus*, and *Equus*, of which the last was as large as the living horse. The remarkably oriental character of this fauna is worthy of special notice. At the eastern base of the Rocky Mountains in Colorado a group of sandstones (Denver beds) has yielded a large species of bison. Again, abundant remains of *Aceratherium* have recently been found in the Pliohippus beds of the Upper Pliocene series of Kansas.[3]

Australia.—In New South Wales, during what are supposed to correspond with the later Miocene, Pliocene, and Pleistocene periods, the land appears to have been gradually rising and to have been exposed to prolonged denudation and, in the Middle Pliocene period, to great volcanic activity. Hence successive fluviatile terraces were formed and eroded in the valleys, and were in many cases buried under great streams of lava. It is in these buried river-beds that the "deep-leads" lie, from which such large quantities of gold are obtained. They have preserved with wonderful perfection remains of the flora and fauna of the period. Among the plants are large trunks, branches, and fruits of trees, and ferns. With these are associated fresh-water shells, traces of beetles, and bones of a number of extinct marsupials, some of which were distinguished by their great size. One of the most abundant and remarkable of these creatures was the *Diprotodon*, which attained the bulk of a rhinoceros or hippopotamus. Another is the *Nototherium*, probably somewhat like a large tapir, of which three species have been named. An extinct gigantic kangaroo (*Macropus Titan*) had a skull twice as long as that of the largest living species. There were also wombats (*Phascolomys*), and a marsupial lion (*Thylacoleo*), with the marsupial hyæna (*Thylacinus*), and *Sarcophilus* or "devil," which still live in Tasmania. To these may be added the *Dromornis*—a large bird represented now by the emu.[4]

In Victoria a younger Tertiary series overlies the older volcanic rocks referred to on p. 1003, and is likewise associated with newer volcanic ejections. It includes both marine and fluviatile deposits. The marine group, with species of *Trigonia*, *Haliotis*, *Cerithium*, *Waldheimia*, &c., is found up to heights of 1000 feet above sea-level. The fluviatile deposits, besides auriferous gravels, include also beds of lignite with abundant remains of terrestrial vegetation, and have yielded remains of *Diprotodon*, *Phascolomys*, *Thylacoleo*, *Macropus*, *Procoptodon*, *Dasyurus*, *Hypsiprimnus*, *Canis dingo*, &c. Vast sheets of basaltic and doleritic lavas have overspread the plains and filled up the Pliocene river-beds.[1]

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[1] Blanford, *Brit. Assoc.* 1880, p. 578, and 1884, Address.

[2] A. Heilprin, as cited on p. 981.

[3] Marsh, *Amer. Journ. Sci.* xxxiv. (1887) p. 323.

[4] C. S. Wilkinson, 'Notes on Geology of New South Wales,' Sydney, 1882.

In Queensland the presence of Tertiary rocks is inferred rather than proved. But from the similarity of the volcanic rocks of that colony to those of Victoria and New South Wales, it is believed that the older and newer volcanic groups which have been established are likewise of Tertiary age.[2]

New Zealand.—Deposits referable to the Pliocene division of the geological record play an important part in the geology and industrial development of New Zealand. According to Sir J. Hector, they belong to a time when the land was much more extensive than it now is, and when in the North Island volcanic action reached its greatest activity. Some of the beds were formed on the sea-floor, and contain in abundance *Rotella zealandica*, with *Dosinea anus*, *Struthiolaria Fraseri*, *Buccinum maculatum*. From 70 to 90 per cent of the mollusca are of still living species. In the South Island, the Pliocene strata are to a large extent unfossiliferous gravels, such as those of the Canterbury Plains and the Monteri Hills, in Nelson, which were derived from the mountainous interior. That considerable terrestrial disturbance took place during and subsequent to the deposit of the Pliocene series is shown by the disturbed and elevated positions of the beds in some places. Here and there the marine strata have been raised to a height of 300 feet (near Napier to more than 2000 feet) above the sea without disturbance of their horizontal position ; but elsewhere they have been completely overturned. The economic importance of these deposits arises mainly from their yielding the richest supplies of alluvial gold.[3]

PART V. POST-TERTIARY OR QUATERNARY.

This portion of the Geological Record includes the various superficial deposits in which nearly all the mollusca are of still living species. It is usually subdivided into two series: (1) an older group of deposits in which many of the mammals are of extinct species,—to this group the names Pleistocene, Post-Pliocene, and Diluvial have been given ; and (2) a later series, wherein the mammals are all, or nearly all, of still living species, to which the names Recent, Alluvial, and Human have been assigned. These subdivisions, however, are confessedly very artificial, and it is often exceedingly difficult to draw any line between them. The names assigned to them also are not free from objection. The epithet "human," for example, is not strictly applicable only to the later series of deposits, for it is quite certain that man coexisted with the fauna of the Pleistocene series.

In Europe and North America a tolerably sharp demarcation can usually be made between the Pliocene formations and those now to be described. The Crag deposits of the south-east of England, as we have seen, show traces of a gradual lowering of the temperature during later

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[1] R. A. F. Murray, 'Geology of Victoria,' p. 113.

[2] These volcanic accumulations are extensive and of great interest. They have been described by Mr. R. L. Jack in the 'Geology and Palæontology of Queensland,' chap. xxxv.

[3] Hector, 'Handbook of New Zealand,' p. 26 ; Hutton, *Quart. Journ. Geol. Soc.* 1885, p. 211.

Pliocene times, and the same fact is indicated by the Pliocene fauna and flora on the Continent even in the Mediterranean basin. This change of climate continued until at last thoroughly Arctic conditions prevailed, under which the oldest of the Post-Tertiary or Pleistocene deposits were accumulated in northern and central Europe, and in Canada and the northern part of the United States.

It is hardly possible to arrange the Post-Tertiary accumulations in a strict chronological order, because we have no means of deciding, in many cases, their relative antiquity. In the glaciated regions of the northern hemisphere the various glacial deposits are grouped as the older division of the series under the name of Pleistocene. Above them, lie younger accumulations such as river-alluvia, peat-mosses, lake-bottoms, cave-deposits, blown-sand, raised lacustrine and marine terraces, which, merging insensibly into those of the present day, are termed Recent or Prehistoric.

Section i. Pleistocene or Glacial.

§ 1. General Characters.

Under the name of the Glacial Period or Ice Age, a remarkable geological episode in the history of the northern hemisphere is denoted.[1] The Crag deposits (p. 1008) afford evidence of a gradual refrigeration of climate at the close of the Tertiary ages. This change of temperature affected the higher latitudes alike of the Old and the New World. It reached such a height that the whole of the north of Europe was buried under ice, which, filling up the basins of the Baltic and North Sea, spread over the plains even as far south as close to the site of London, and in Silesia and Gallicia to the 50th parallel of latitude. Beyond the limits reached by the northern ice-sheet, the climate was so arctic that snow-fields and glaciers spread even over the comparatively low hills of the Lyonnais and Beaujolais in the heart of France. The Alps were loaded with vast snow-fields, from which enormous glaciers descended into the plains, overriding ranges of minor hills on their way. The Pyrenees were in like manner covered, while snow-fields and glaciers extended southwards for some distance over the Iberian peninsula. In North America also, Canada and the eastern States of the American Union down to about the 39th parallel of north latitude, lay under the northern ice-sheet.

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[1] No section of geological history now possesses a more voluminous literature than the Glacial Period, especially in Britain and North America. For general information the student may refer to Lyell's 'Antiquity of Man,' J. Geikie's 'Great Ice Age,' 'Prehistoric Europe,' Address to Geological Section of British Association, 1889, and paper in *Trans Roy. Soc. Edin.* xxxvii. part i. (1893) p. 127; J. Croll's 'Climate and Time,' 'Discussions on Climate and Cosmology'; A. Penck, 'Vergletscherung der Deutschen Alpen,' 1882; J. Partsch, 'Die Gletscher der Vorzeit in den Karpathen, &c.,' 1882; A. Falsan and E. Chantre, 'Anciens Glaciers, &c., de la partie moyenne du Bassin du Rhône,' 1879, and for detailed descriptions, to the *Quart. Journ. Geol. Soc.*, *Geol. Mag.*, *Zeitsch. Deutsch. Geol. Ges.*, *Jahrb. Preuss. Geol. Landesanst.*, *Amer. Journ. Science*, *Annual Reports U.S. Geol. Surv.*, *Bull. Amer. Geol. Soc.*, for the last fifteen or twenty years.

The effect of the movement of the ice was necessarily to remove the soils and superficial deposits of the land-surface. Hence, in the areas of country so affected, the ground having been scraped and smoothed, the glacial accumulations laid down upon it usually rest abruptly, and without any connection, on older rocks. Considerable local differences may be observed in the nature and succession of the different deposits of the glacial period, as they are traced from district to district. It is hardly possible to determine, in some cases, whether certain portions of the series are coeval, or belong to different epochs. But the following leading facts have been established. First, there was a gradual increase of the cold, until the conditions of modern North Greenland extended as far south as Middlesex, Wales, the south-west of Ireland, and 50° N. lat. in central Europe, and about 39° N. lat. in eastern America. This was the culmination of the Ice Age,—the first or chief period of glaciation. Then followed an interval or interglacial period, during which the climate seems to have become much milder. This interlude was succeeded by another cold period, marked by a renewed augmentation of the snow-fields and glaciers,—a second period of glaciation.

It has been maintained by some observers that as many as four or five distinct epochs of cold are included within the geological interval represented by the Pleistocene deposits. Other writers contend for the essential unity of the glacial period. The truth will probably be found to lie somewhere between the extreme views. There seems to be demonstrable proof that there was at least one interglacial period. There may have been more than one advance of the northern ice into temperate latitudes. The interval of milder climate, of which there is clear proof, must have been of such prolonged duration that southern types of plant and animal life were enabled to spread northward and resume their former habitats.[1] Eventually, however, and no doubt very gradually, after intervals of increase and diminution, the ice finally retired towards the north, and with it went the Arctic flora and fauna that had peopled the plains of Europe, Canada, and New England. The existing snow-fields and glaciers of the Pyrenees, Switzerland, and Norway are remnants of the great ice-sheets of the glacial period, while the Arctic plants that people the mountains, and survive in scattered colonies on the lower grounds, are relics of the northern vegetation that covered Europe from Norway to Spain.

The general succession of events has been the same throughout all the European region north of the Alps, likewise in Canada, Labrador, and the north-eastern States, though of course with local modifications. The following summary embodies the main facts in the history of the Ice Age. Some local details are given in subsequent pages.

Pre-glacial Land-surfaces.—Here and there, fragments of the land over which the ice-sheets of the glacial period settled have escaped the general extensive ice-abrasion of that ancient terrestrial surface, and have even retained relics of the forest growth that covered them. One of the best-known deposits in which these relics have been preserved is the so-called "Forest Bed" (p. 1013). Above that deposit, as already described (p. 1014), there is seen, here and there, on the Norfolk coast, a local or intermittent bed of clay containing remains of Arctic plants (*Salix polaris*, *Betula nana*, &c., Fig. 454), together with the little marmot-like rodent *Spermophilus*. These relics of a terrestrial vegetation are drifted specimens, but they cannot have travelled far, and they probably represent a portion of the Arctic flora which had already found its way into the middle of England before the advent of the ice-sheet. Judging from the present distribution of the same plants, we may infer that the climate had become about 20° colder than it was during the time represented by the Forest bed—a difference as great as that between Norfolk and the North Cape at the present day.[1]

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[1] Those who wish to enter into this debated subject will find it discussed from opposite sides in some recent papers by T. C. Chamberlin and G. F. Wright in the *Amer. Journ. Sci.* (1892, 1893) with references to other authorities.

The Northern Ice-sheet.—At the base of the glacial deposits, the solid rocks over the whole of northern Europe and America present the characteristic smoothed flowing outlines produced by the grinding action of land-ice (p. 428). The rock-surfaces that look away from the quarter whence the ice moved are usually rough and weatherworn (Leeseite), while those that face in that direction (Stoss-seite) are all ice-worn. Even on a small boss of rock or along the side of a hill, it is commonly not difficult to tell which way the ice flowed, by noting towards which point the striæ run and the rough faces look. Long exposed, the peculiar ice-worn surface is apt to be effaced by the disintegrating action of the weather, though it retains its hold with extraordinary pertinacity. Along the fjords of Norway and the sea-lochs of the west of Scotland, it may be seen slipping into the water, smooth, bare, polished, and grooved, as if the ice had only recently retreated. Inland, where a protecting cover of clay or other superficial deposit has

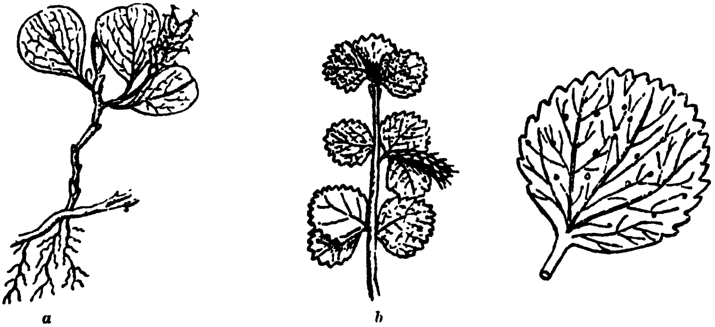

Fig. 454.—Arctic Plants found in Glacial Deposits.
a, Salix polaris, Wahlenb. (⅔); *b*, Betula nana, Linn.; *c*, Leaf of same, showing the size to which it grows in more southern countries.

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[1] C. Reid, *Horizontal Section, No.* 127 *of Geol. Survey*, and "Geology of the Country around Cromer" (sheet 68 E.), in *Memoirs of Geol. Survey*, 1882.

been newly removed, the peculiar ice-worn surface may be as fresh as that by the side of a modern glacier.

From the evidence of these striated rock-surfaces and the scattered blocks of rock that were transported to various distances, it has been ascertained that the whole of northern Europe was buried under one continuous mantle of ice. The southern edge of the ice-sheet must have lain to the south of Ireland, whence it passed along the line of the Bristol Channel, and thence across the south of England, keeping to the north of the valley of the Thames. The whole of the North Sea was filled with ice down to a line which ran somewhere between the coast of Essex and the present mouths of the Rhine, eastwards along the base of the Westphalian hills, and round the projecting promontory of the Harz, whence it swung to the base of the Thuringerwald and struck eastwards across Saxony, keeping to the north of the Erz, Riesen and Sudeten mountains; thence across Silesia, Poland and Gallicia by way of Lemberg, and circling round through Russia by Kieff and Nijni Novgorod northwards by the head of the Dvina to the Arctic Ocean. The total area of Europe thus buried under ice has been computed to have been not less than 770,000 square miles.

Owing mainly to the direction of the prevalent moisture-bearing winds, the snowfall was greatest towards the west and north-west, and in that direction the ice-sheet attained its greatest thickness. Over Scandinavia, which was probably entirely buried beneath the icy covering, it was perhaps between 6000 and 7000 feet thick. Thence the sheet spread southwards, gradually diminishing in thickness. But from the striæ left by it on the Harz, it is computed to have been at least 1470 feet thick where it abutted on that ridge. The Scandinavian ice joined that which spread over Britain, where the dimensions of the sheet were likewise great. Many mountains in the Scottish Highlands show marks of the ice-sheet at heights of 3000 feet and more. If to this depth we add that of the deep lakes and fjords which were filled with ice, we see that the sheet could not have been less than 5000 feet thick in the northern parts of Britain.

This vast icy covering, like the Arctic and Antarctic ice-sheets of the present day, was in continual motion, slowly draining downwards to lower levels. Towards the west, its edge reached the sea, as in Greenland now, and must have advanced some distance along the sea-floor until it broke off into bergs that floated away northward. Towards the south and east it ended off upon land, and no doubt discharged copious streams of glacier-water over the ground in its front. In North America the southern edge of the ice-sheet is sometimes marked by a "terminal moraine"—a feature well displayed from Pennsylvania to Dakota.

The directions of movement of the ice-sheets can be followed by the evidence (1st) of striæ graven on the rocks over which the ice passed, and (2nd) of transported stones ("erratic blocks") which can be traced back to their original sources.

In Europe the great centre of dispersion for the ice-drainage was the table-land of Scandinavia. As shown by the rock-striæ in Sweden and

Norway, the ice moved off that area northwards and north-eastwards across northern Finland into the Arctic Ocean; westwards into the Atlantic Ocean, south-westwards into the basin of the North Sea; southward, south-westward, and south-eastward across Denmark and the low plains of Holland, Germany, and Russia, and the basins of the Baltic, Gulf of Bothnia, and Gulf of Finland. The evidence of the transported stones coincides with that of the striation, and is often available when the latter is absent.

United with the Scandinavian ice, but having an independent system of drainage, was the ice-sheet that covered nearly the whole of Britain. The rock-striæ show that while it probably buried the country even over its highest mountain-tops, it moved outward from each chief mass of high ground. Thus, from the Scottish Highlands, which were the main gathering ground, it drained northward to join the Norwegian ice, and move with it in a north-westerly direction across the Orkney and Shetland Islands. Westward it descended into the Atlantic; eastwards into the basin of the North Sea, to merge there also into the Scandinavian sheet and that which streamed off from the high grounds of the south of Scotland, and to move as one vast ice-field in a south-south-west direction across the north-east and east of England. Southwards it flowed into the basin of the Clyde and the Irish Sea, to unite with the streams moving from the south-west of Scotland and the north-west of England and Wales. The centre of Ireland appears also to have been an area from which the ice moved outwards, passing into the Atlantic on the one side and joining the British ice-fields on the other.

It is when we follow the direction of the ice striæ, and see how they cross important hill ranges, that we can best realise the massiveness of the ice-sheet and its resistless movement. As it slid off the Scottish Highlands, for instance, it went across the broad plains of Perthshire, filling them up to a depth of at least 2000 feet, and passing across the range of the Ochil Hills, which at a distance of twelve miles runs parallel with the Highlands, and reaches a height of 2352 feet. Mountains of 3000 feet and more, with lakes at their feet, 600 feet deep, have been well ice-worn from top to bottom. It has been observed that the striæ along the lower slopes of a hill-barrier run either parallel with the trend of the ground or slant up obliquely, while those on the summits may cross the ridge at right angles to its course, showing a differential movement in the great ice-sheet, the lower parts, as in a river, becoming embayed, and being forced to move in a direction sometimes even at a right angle to that of the general advance. On the lower grounds, also, the striæ, converging from different sides, unite at last in one general trend as the various ice-sheets must have done when they descended from the high grounds on either side and coalesced into one common mass. This is well seen in the great central valley of Scotland. Still more marked is the deflection of, the striæ in the basin of the Moray Firth. Northwards they are deflected in a N.N.W. direction across Caithness and the Orkney Islands, pointing to the influence of the Scandinavian ice-sheet. On the south side of the basin, they run E. by

S., and at last S.E., on the north-east of Aberdeenshire, showing that the ice there turned southwards into the North Sea, until it met the N.E. stream from Kincardineshire and the valleys of the Dee and Don, with which and with the ice from Scandinavia it turned southward into the basin of the North Sea. The great mass of ice which crept down the basin of the Firth of Clyde was joined by that which descended from the uplands of Carrick and Galloway, and the united stream filled up the Irish Sea and passed over the north of Ireland. At that time England and the north-west of France were probably united, so that any portion of the North Sea basin not invaded by land-ice would form a lake, with its outlet by the hollow through which the Strait of Dover has since been opened.

When this glaciation took place the terrestrial surface of the northern hemisphere had acquired the main configuration which it presents to-day. The same ranges of hills and lines of valley which now serve to carry off the rainfall served then to direct the results of the snowfall seawards. The snow-sheds of the Ice Age probably corresponded essentially with the water-sheds of the present day. Yet there is evidence that the coincidence between them was not always exact. In some cases the snow and ice accumulated to so much greater a depth on one side of a ridge than on the other that the flow actually passed across the ridge, and detritus was carried out of one basin into another. A remarkable instance of this kind has been observed in the north of Scotland, where so thick was the ice-sheet that fragments of rock from the centre of Sutherland have been carried up westward across the main water-parting of the country and have been dropped on the western side.[1]

In North America also abundant evidence is afforded of a northern ice-sheet which overrode Canada and the eastern States southwards to about the 39th parallel of latitude in the valley of the Missouri. Some details regarding the area which it covered and the traces it has left of its presence are given at p. 1050.

Beyond the limits of the northern ice-sheet, the European continent nourished snow-fields and glaciers wherever the ground was high enough and the snowfall heavy enough to furnish them. As already mentioned, the precipitation of moisture during the Ice Age, as at present, was greatest towards the west, and consequently in the western tracts the independent snow-fields and glaciers were most numerous and extensive. Even at the present time, the glaciers of the western part of the Alpine chain are larger than those farther east. At the time of the northern ice-sheet a similar local difference existed. The present snow-fields and glaciers of these mountains, large though they are, form no more than the mere shrunken remnants of the great mantle of snow and ice which then overspread Switzerland. In the Bernese Oberland, for example, the valleys were filled to the brim with ice, which, moving northwards, crossed the great plain, and actually overrode a part of the Jura Mountains; for huge fragments of granite and other rocks from the central chain of the Alps are found high on the slopes of that range of heights. The Rhone glacier swept westward across all the intervening ridges and valleys, and left its moraine-heaps in the valley of the Rhone where Lyons now stands. At the same time the high grounds of the Lyonnais, Beaujolais, and Auvergne (lat. 45° S.) had their glaciers. Others flourished on the Iberian tableland, at least as far south as the basin of the Douro (lat. 41°). Eastwards in corresponding latitudes glacier relics become scantier and disappear. The Vosges possessed a group of glaciers which have left behind them some beautifully perfect moraines. Less extensive were those of the Black Forest, Sudetengebirge, and Carpathians. No trace of glaciation has been detected in the Balkans. A similar relation between snowfall and glaciation is traceable in North America, but there it is the eastern area which supported the massive ice-sheets, while the western plateaux and mountain-ranges, which were probably then, as now, comparatively arid, had only valley-glaciers.

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[1] Peach and Horne, *Brit. Assoc.* 1892, p. 720.

That the ice in its march across the land striated even the hardest rocks by means of the sand and stones which it pressed against them, is a proof that, to some extent at least, the terrestrial surface must have been at this time abraded and lowered in level. How far this erosion proceeded, or, in other words, how much of the undoubtedly enormous denudation everywhere visible over the glaciated parts of Europe, is attributable to the actual work of land-ice, is a problem which may never be even approximately solved. There seems good ground for the belief that a thick cover of rotted rock—the result of ages of previous subaerial waste—lay over the surface, and that the "glacial deposits" consist in great measure of this material, moved and reassorted by ice and water (pp. 351, 431). The land, as above remarked, had the same general features of mountain, valley, and plain as it has now, even before the ice settled down upon it. But the prominences reached by the ice were rounded off and smoothed over, the pre-glacial soils and covering of weathered rock were in large measure ground up and pushed away, the valleys were correspondingly deepened and widened, and the plains were strewn with ice-borne débris. It is obvious that the influence of the moving ice-sheets has been far from uniform upon the rocks exposed to it, this variation arising from the differences in powers of resistance of the rocks on the one hand, and in the mass, slope, and grinding power of the ice on the other. Over the lowlands, as in central Scotland and much of the north German plain, the rocks are for the most part concealed under deep glacial débris. But in the more undulating hilly ground, particularly in the north and north-west, the ice has effected the most extraordinary abrasion. It is hardly possible, indeed, to describe adequately in words these regions of most intense glaciation. The old gneiss of Norway and Sutherlandshire, for example, has been so eroded, smoothed, and polished, that it stands up in endless rounded hummocks, many of them still smooth and curved like dolphins' backs, with little pools, tarns, and larger lakes lying between them. Seen from a height the ground appears like a billowy sea of cold grey stone. The lakes, each lying in a hollow of erosion, seem scattered broadcast over the landscape. So enduring is the rock, that, even after the lapse of so long an interval, it retains its ice-worn aspect almost as unimpaired as if the work of the glacier had been done only a few generations since.[1] The abundant smoothed and striated rock-basin lakes of the northern parts of Europe and North America are a striking evidence of ice-action (pp. 430, 1086). The phenomenon of "giants' kettles," characteristic of glaciated rock-surfaces in Sweden, Silesia, and Switzerland (p. 429), is another mark of the same process of erosion.

Ice-crumpled Rocks.—Not only has the general surface of the land been abraded by the ice-sheets, but here and there more yielding portions of the rocks have been broken off or bent back, or corrugated by the pressure of the advancing ice. Huge blocks 300 yards or more in length have been bodily displaced and launched forward on glacial detritus. Such are some of the enormous masses of chalk displaced and imbedded in the drift of the Cromer cliffs, and the transported sheets of Lincolnshire Oolite found in Leicestershire.[2] The laminæ of shales or slates are observed to be pushed over or crumpled in the direction of ice-movement. Occasionally tongues of the glacial detritus which was simultaneously being pressed forward under the ice have been intruded into cracks in the strata, so as to resemble veins of eruptive rock.[3]

Detritus of the Ice-sheet—Boulder-clay—Till.—Underneath the great ice-sheet, and probably partly incorporated in the lower portions of the ice,[4] there accumulated a mass of earthy, sandy, and stony matter (till, boulder-clay, "grundmoräne," "moraine-profonde," "older diluvium") which, pushed along and ground up, was the material wherewith the characteristic flowing outlines and smoothed striated surfaces were produced.[5] This "glacial drift" spreads over the low grounds that were buried under the northern ice-sheet, resting usually on surfaces of rock that have been worn smooth, disrupted, or crumpled by ice. It is not spread out, however, as a uniform sheet, but varies greatly in thickness and in irregularity of surface. Especially round the mountainous centres of dispersion, it is apt to occur in long ridges ("drums," or "drumlins"), which run in the general direction of the rock-striation, that is, in the path of the ice-movement. It may be traced up many valleys into the mountains, underlying the moraines of the later glaciation. In other valleys, it has been removed by the younger glaciers. In most glaciated countries the boulder-clay is not one continuous deposit, but may be separated into two or more distinct formations, which lie one on the other, and mark distinct and successive periods of time.

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[1] Some of these *roches moutonnées* may be of Palæozoic age (*Nature*, August 1880).

[2] Mr. Fox Strangways has noticed one such sheet near Melton which measures at least 300 yards in length by 100 in breadth, but may extend beneath the boulder-clay to a greater distance. Report of Geological Survey of the United Kingdom, *Science and Art Report* for 1892, p. 249.

[3] On the disruption of the Chalk below the Till of Cromer see C. Reid on Geology of Cromer, *Mem. Geol. Surv.* 1882. For analogous phenomena at Möens Klint, off the coast of Denmark, see Johnstrup, *Zeit. Deutsch. Geol. Ges.* xxvi. (1874) p. 533. Compare also H. Credner, *op. cit.* xxxii. (1880) p. 75. F. Wahnschaffe, *op. cit.* xxxiv. (1882) p. 562.

[4] Bruckner, *Penck's Geographische Abhandl.* Band I. Heft 1.

[5] As already suggested, the materials of the till may have consisted largely of a layer of decomposed rock due to prolonged pre-glacial disintegration (pp. 351, 431). It is difficult to explain by any known glacial operation the accumulation of such deep masses of detritus below a sheet of moving land-ice. Another problem is presented by the occasional and sometimes extensive preservation of undisturbed loose pre-glacial deposits under the till. The way in which the "Forest-bed" group has escaped for so wide a space under the Cromer cliffs, with their proofs of enormous ice movement, is a remarkable example.

In those areas which served as independent centres of dispersion for the ice-sheet, boulder-clay partakes largely of the local character of the rocks of each district where it occurs. Thus in Scotland, the clay varies in colour and composition as it is traced from district to district. Over the Carboniferous rocks it is dark, over the Old Red Sandstones it is red, over the Silurian rocks it is fawn-coloured. The material of the deposit is generally an earthy or stony clay, which in the lower parts is often exceedingly compact and tenacious. The higher portions are frequently loose in texture, but alternations of hard tough clay and more friable material may be met with in the same deposit. In general, boulder-clay is unstratified, its materials being irregularly and tumultuously heaped together. But rude traces of bedding may not infrequently be detected, while in some cases, especially in the higher clays, distinct stratification may be observed.

The great majority of the stones in boulder-clay are of local origin, not always from the immediately adjacent rocks, but from points within a distance of a few miles. Evidence of transport can be gathered from the stones, for they are found in almost every case to include a proportion of fragments which have come from a distance. The direction of transport indicated by the percentage of travelled stones agrees with the traces of ice-movement as shown by the rock-striæ. Thus, in the lower part of the valley of the Firth of Forth, while most of the fragments are from the surrounding Carboniferous rocks, from 5 to 20 per cent have come eastward from the Old Red Sandstone range of the Ochil Hills—a distance of 25 or 30 miles—while 2 to 5 per cent are pieces of the Highland rocks, which must have come from high grounds at least 50 miles to the north-west. The farther the stones in the till have travelled, the smaller they usually are. As each main mass of elevated ground seems to have caused the ice to move outward from it for a certain distance, until the stream coalesced with that descending from some other height, the bottom-moraine or boulder-clay, as it was pushed along, would doubtless take up local débris by the way, the detritus of each district becoming more and more ground up and mixed, until of the stones from remoter regions only a few harder fragments would be left. In cases where no prominent ridges interrupted the march of the ice-sheet, and where the ground was low and covered with soft loose deposits, blocks of hard crystalline rocks might continue to be recognisable far from their source. Thus in the stony clay and gravel of the plains of Northern Germany and Holland, besides the abundant locally-derived detritus, fragments occur which have had an unquestionably northern origin. Some of the rocks of Scandinavia, Finland, and the Upper Baltic are of so distinctive a kind that they can be recognised in small pieces. The peculiar syenite of Laurwig, in the south of Norway, has been found abundantly in the drift of Denmark; it occurs also in that of Hamburg, and has been detected even in the boulder-clay of the Holderness cliffs in Yorkshire. The well-known rhombenporphyr of southern Norway has likewise been recognised at Cromer and in Holderness. Fragments of the Silurian rocks from Gothland, or from the Russian islands Dago or Oesel, are scattered abundantly through the drift of the North German plain, and have been met with as far as the north of Holland. Pieces of granite, gneiss, various schists, porphyries, and other rocks, probably from the north of Europe, occur in the till of Norfolk.[1] These transported fragments are an impressive testimony to the movements of the northern ice. No Scandinavian blocks have been met with in Scotland, for the Scottish ice was massive enough to move out into the basin of the North Sea, until it met the northern ice-sheet streaming down from Scandinavia, which was thereby kept from reaching the more northerly parts of England.

The stones in boulder-clay have a characteristic form and surface. They are usually oblong, have one or more flat sides or "soles," are smoothed or polished, and have their edges worn round (Fig. 160). Where they consist of a fine-grained enduring rock, they are almost invariably striated, the striæ running on the whole with the long axis of the stone, though one set of scratches may be seen crossing and partially effacing another, which would necessarily happen as the stones shifted their position under the ice. These markings are precisely similar to those on the solid rocks underneath the boulder-clay, and have manifestly been produced in the same way by the mutual friction of rocks, stones, and grains of sand as the whole mass of débris was being steadily pushed on in one general direction.

As above remarked, boulder-clay is not always one continuous deposit. On the contrary, when a sufficiently large extent of it is examined, evidence can commonly be found of two distinct divisions, sometimes even of more than two. These are separable from each other by differences of colour, composition, and texture. An attentive study of them shows that they have been formed successively under ice-sheets moving often from different directions and transporting different materials. Their limits of distribution also vary, the lower and older subdivisions extending farther south and spreading over a wider area than the upper.

Interglacial Beds.—That the deposition of boulder-clay in Britain was interrupted by milder intervals, when the ice, partially at least, retreated from the land and allowed trees and other vegetation to grow up to heights of 800 or 900 feet above the sea, was first proved by observations at Chapel Hall, Lanarkshire.[1] During the thirty years which have intervened since these observations were published, a large amount of additional information on this subject has been collected in the British Islands, on the continent of Europe, and in North America. The boulder-clays are now well known to be split up with inconstant and local stratifications of sand, gravel and clay, often well stratified, pointing to conditions quite distinct from those under which ordinary boulder-clay was accumulated. These intercalations have been recognised as bearing witness to intervals when the ice retired from some districts and when ordinary water-action came into play over the ground-moraine thus exposed. Much controversy, however, has arisen as to the chronological value to be assigned to these intervals. To some geologists the intercalations in the boulder-clay appear to indicate little more than seasonal variations in the limits and thickness of the ice-sheets, such as now affect the glaciers of Scandinavia and the Alps. To others, again, they furnish proof of successive interglacial periods by which the long Ice Age was broken up. Thus Professor James Geikie, recently reviewing the whole evidence on the subject, has come to the conclusion that there were really five glacial intervals embraced within what is called the Glacial Period, separated from each other by four interglacial periods of mild temperature.[2]

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[1] These erratics, from their petrographical characters, appear to me to be certainly not from Scotland. Had that been their source they could not have failed to be accompanied by abundant fragments of the rocks of the south of Scotland, which are continuously absent. See V. Madsen, *Quart. Journ. Geol. Soc.* xlix. (1893) p. 114.

Much difficulty in forming definite conclusions as to the importance of these obvious interruptions in the deposition of the boulder-clay arises from the absence of continuous sections wherein the order of succession of the several stages of the glacial history can be demonstrated by visible relations of superposition. A section at one locality has to be correlated with another at a greater or less distance, and assumptions have to be made as to the identity or difference of the various deposits. The evidence of fossils can hardly be said to be available, for it is so fragmentary as to give little aid in determining the chronology of the deposits in which it occurs.

The existence of two distinct deposits of boulder-clay, with an intervening group of sands, gravels, clays, and peat-beds, may be taken to afford good proof of two advances and retreats of the ice-sheets, with an interval of non-glacial conditions between them. The oldest boulder-clay marks the greatest extent of the ice. The upper boulder-clay shows that though the ice on returning attained huge dimensions and formed continuous ice-sheets over much of northern Europe, it did not descend as far as at first. Yet while these two main epochs of maximum cold can be satisfactorily established there appears to be no reason to doubt that each of them may have had fluctuations in temperature or in snowfall, so that the ice-sheets may have alternately or intermittently advanced and retreated over considerable tracts of country. The ground-moraine, when thus laid bare, may have been reassorted by water, so that as the ice once more moved forward, it here and there pushed its detritus over the aqueous deposits of the milder interval. But the marked contrast between the lower and upper boulder-clay in composition and extent shows that the interval which separated them was probably of prolonged duration. We have here evidence of at least one important interglacial period. The occurrence of such interludes of more genial climate is what might be expected to be traceable on the astronomical theory of the cause of the Ice Age, which has been already discussed (p. 24). The deposits which record the passage of an interglacial period consist of layers of sand and gravel, such as, over a wide area of central England, separate the two boulder-clays, also deposits of clay and beds of peat found elsewhere in a similar position. To this age also have been assigned the older alluvial terraces which have been preserved chiefly beyond the limits of the second glaciation, and from which a considerable number of mammalian remains as well as stone implements of human workmanship have been disinterred.

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[1] A. G. *Trans. Geol. Soc. Glasgow*, vol. i. part ii. (1863).

[2] *Trans. Roy. Soc. Edin.* xxxvii. part i. (1893) p. 146.

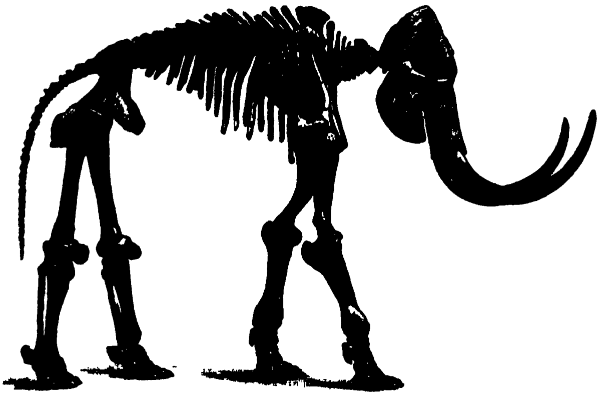

Fig. 455.—Mammoth (*Elephas primigenius*).
From the Skeleton in the Musee Royal, Brussels (much reduced).

During interglacial conditions the climate in the northern hemisphere was probably much more equable and mild than at present, with a higher mean temperature and at certain intervals a greater precipitation of moisture.[1] From the general aspect of the flora and fauna preserved in interglacial deposits in Britain it may perhaps be inferred that there was then more sunshine than now. Mr. Reid suggests that the scarcity of thoroughly aquatic mollusks and of fish indicates that during some stages, at least, the climate was dry rather than moist. As a result of more favourable meteorological conditions vegetation flourished even far north where it can now hardly exist. The frozen tundras of Siberia appear then to have supported forests which have long since been extirpated, the present northern limit of living trees lying far to the southward. Indications of a more equable and milder climate are likewise supplied by the plant-remains found in Pleistocene tufas of different parts of

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[1] J. Croll, *Phil. Mag.* 1885, p. 36.

Europe, where species now restricted to more southern countries were then able to flourish together with those which are still native there.[1]

The fauna of the northern parts of our hemisphere was then an extraordinary one. It was marked more especially by the presence of the last of the huge pachyderms, which had for so many ages been the lords of the European forests and pastures. The hairy mammoth and woolly rhinoceros roamed over the plains of Siberia and across most, if not the whole, of Europe. These animals were probably driven southward by the increasing cold, and they appear to have survived some of the advances of the ice, returning into their former haunts when a less wintry climate allowed the vegetation on which they browsed once more to overspread the land.[2] Some of the mammals now restricted to the far north likewise found their way into countries from which they have long disappeared. The reindeer migrated southwards into Switzerland,[3] the glutton into Auvergne, while the musk-sheep and Arctic fox travelled certainly as far as the Pyrenees. As the climate became less chilly, animals of a more southern type advanced into Europe: the porcupine, leopard, African lynx, lion, striped and spotted hyænas, African elephant, and hippopotamus. With each oscillation of climate there would be a corresponding immigration and emigration of northern and southern types.

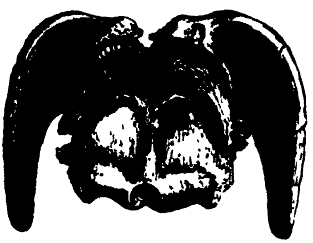

Fig. 456.—Back View of Skull of Musk-sheep (*Ovibos moschatus*, ⅙) brick-earth, Crayford, Kent.

Evidences of Submergence.—After the ice had attained its greatest development, some portions of north-western Europe, which had perhaps stood at a higher level above the sea than they have done since, began to subside. The ice-fields were carried down below the sea-level, where they broke up and cumbered the sea with floating bergs. The heaps of loose débris which had gathered under the ice, being now exposed to waves, ground-swell, and marine currents, were thereby more or less washed down and reassorted. Coast-ice, no doubt, still formed along the shores, and was broken up into moving floes, as happens every year now in northern Greenland. The proofs of this phase of the long glacial period are contained in shell-bearing sands, gravels, and clays which overlie the coarse older till, and are perhaps, to some extent, furnished by erratic blocks.[1] It is difficult to determine the extent of the submergence, for, when the land rose, the more elevated portions continued to be seats of glaciers, which, moving over the surface, destroyed the deposits that would otherwise have remained as witnesses of the presence of the sea, while at the same time the great bodies of water discharged from the retreating glaciers and snow-fields must have done much to reassort the detritus on the surface of the land. From the evidence of marine shells, southern Scandinavia is believed to have sunk about 600 feet below its present level. In Britain the submergence was probably not less than 500 feet. If indeed we take the beds of marine shells which have been found in North Wales, Cheshire, and elsewhere as marking actual sea-bottoms, the depression which they would then indicate must have been at least 1350 feet. But these shelly deposits are probably not conclusive proofs of submergence.[2]

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[1] Nathorst, *Engler's Botanische Jahrb.* 1881, p. 431; C. Schröter, 'Die Flora der Eiszeit,' Zürich, 1883.

[2] The mammoth lived in the neighbourhood of the extinct volcanoes of central Italy, which were then in full activity. From discoveries in Finland, it has been inferred that the extinction of this animal may not have been much before historical times. A. J. Malmgren, *Oefv. Finsk. Vet. Soc. Forh.* xvii. p. 139. Consult Boyd Dawkins on the range of the mammoth in space and time: *Q. J. Geol. Soc.* xxxv. (1879) p. 138; and Howorth, *Geol. Mag.* 1880; 'The Mammoth and the Flood' and 'The Glacial Nightmare.'

[3] On the distribution of the reindeer at present and in older time, see C. Struckmann, *Zeitsch. Deutsch. Geol. Ges.* xxxii. (1880) p. 728.

That ice continued to float about in these waters is shown by the striated stones contained in the fine clays, and by the remarkably contorted structure which these clays occasionally display. Sections may be seen (as at Cromer) where, upon perfectly undisturbed horizontal strata of clay and sand, other similar strata have been violently crumpled, while horizontal beds lie directly upon them. These contortions may have been produced by the horizontal pressure of some heavy body moving upon the originally flat beds, such as ice in the form of an ice-sheet or of large stranding masses driven aground in the fjords or shallow waters where the clays accumulated; or possibly, in some cases, sheets of ice, laden with stones and earth, sank and were covered up with sand and clay, which, on the subsequent melting of the ice, would subside irregularly. Another indication of the presence of floating ice is furnished by large scattered boulders, lying on the stratified sands and gravels. Though these blocks probably belong as a rule to the time of the chief glaciation, they may in some cases have been shifted about by floating ice during the submergence.

Second Glaciation—Re-elevation—Raised Beaches.—When the land re-emerged from its depression, the temperature all over central and northern Europe was again severe. The northern ice-sheet once more advanced southwards, but did not again attain nearly the same dimensions. From the direction of the striæ, it would appear sometimes to have moved differently from its previous course, occasionally even at right angles to it. In the basin of the Baltic, for example, the later direction of the ice-stream appears to have been south-westwards and westwards. Besides the evidence of this direction furnished by striated rock-surfaces, abundant fragments of the fossiliferous Silurian rocks of Gothland are strewn over the Germanic plain even as far as Holland. There seems no reason to doubt that during this second advance of the ice the Scottish and Scandinavian ice-sheets were again united over what is now the floor of the North Sea. It was then that the upper boulder-clay of Britain was formed. The glaciers of the Alps once more marched outwards over the lower grounds, but without descending so far as before. Their limits are marked by an inner group of moraines.

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[1] For an account of the dispersion of the "erratics" of England and Wales, see Mackintosh, *Q. J. Geol. Soc.* xxxv. (1879) p. 425; and Reports of the Committee appointed to investigate this subject by the British Association, 1872 *et seq.* For those of Scotland much information has been gathered by the Boulder Committee of the Royal Society of Edinburgh; *Proc. Roy. Soc. Edin.* 1872-84. Erratic blocks have probably in the vast majority of cases been dispersed by land-ice, and not by floating ice.

[2] Mere fragments of marine shells in a glacial deposit need not prove submergence under the sea; for they may have been pushed up from the sea-floor by moving ice, as in the case of the shelly till of the west of Scotland, Caithness, Holderness, and Cromer. How far this may have been the origin of the shelly deposits found at high levels in Britain is still a disputed question.

From its second maximum the ice-sheet gradually shrank backward, though probably not without occasional pauses and even advances. As it retreated from the lower grounds it lost the aspect of a continuous ice-sheet, and when it reached the bases of the mountains it eventually separated into valley-glaciers radiating from each principal mass of high ground. In this condition also there was probably a long period of oscillation, the glaciers alternately descending and shrinking backward with variations in the seasons. In Britain there is abundant evidence of this stage in the history of the Ice Age. The Scottish Highlands, being the largest area of high ground in the country, was the chief seat of the ice. Not only did every group of mountains nourish its own glaciers; even small islands, such as Arran and Hoy, had their snow-fields, whence glaciers crept down into the valleys and shed their moraines. It would appear indeed that some of the northern glaciers continued to reach the sea-level even when the land had there risen to near or quite its present elevation. On the east side of Sutherlandshire, at Brora, and on the west side of Ross-shire, at Loch Torridon, the moraines descend to the 50-feet raised beach; at the head of Loch Eriboll, they come down to the sea-level and even extend underneath the water, showing that the glacier at the head of that fjord actually pushed its way into the sea, and no doubt calved its icebergs there.

Another proof of the magnitude of some of the ice-streams that filled the valleys of the Scottish Highlands during the later stages of the Glacial Period is supplied by the proofs that here and there among the loftier or broader snow-fields of the time they accumulated in front of lateral valleys, the drainage of which was in consequence ponded back and made to flow out in an opposite direction by the *col* at the head (p. 423). In these natural reservoirs, the level at which the water stood for a time was marked by a horizontal ledge or platform, due partly to erosion of the hillside, but chiefly to the arrest of the descending débris when it entered the water. The famous "Parallel Roads of Glen Roy" are the most familiar examples. In some instances, as at Achnasheen in Ross-shire, the detritus of the glacial streams was arrested and spread out in broad platforms across the valleys.

The gradual retreat of the glaciers towards their parent snow-fields is admirably revealed by their moraines, perched blocks, and *roches* *moutonnées.* The crescent-shaped moraine-mounds that lie one behind another may be followed up a glen, until they finally die out about the head, near what must have been the edge of the snow-field. The highest mounds, being the last to be thrown down, are often singularly fresh. They frequently enclose pools of water, which have not yet been filled up with detritus or vegetation, or flat peaty bottoms where the process of filling up has been completed. Huge blocks borne from the crags above them are strewn over these heaps, and similar erratics perched on ice-worn knolls on the sides of the valleys mark some of the former levels of the ice. The Scottish Highlands, the southern uplands of Scotland, the hills of the Lake district and of North Wales present admirable examples of all these features.

On the continent of Europe also similar evidence remains of the gradual retreat of the ice. In many tracts of high ground glaciers no longer exist. In the Vosges, for example, they have long since vanished, but fresh moraines remain there as evidence of their former presence. The Alpine glaciers are the lineal descendants of those which filled up the valleys and buried the lowlands of Switzerland and the Lyonnais.

Before the retiring ice-sheet had shrunk into mere valley glaciers, and while it still occupied part of the lower ground, there would doubtless be a copious discharge of water from its melting front. As the ice had overridden the land and buried its minor inequalities, there would be great diversity in the level of the bottom of the ice, and consequently the escaping water would at first flow with little relation to the present main drainage lines. Streams of water might be let loose over the plateaux and hilly ridges as well as over the plains. There could hardly, therefore, fail to be much rearrangement of the detritus left by the ice. Possibly to this part of the Ice Age and to this kind of action we should attribute the masses of gravel and sand which, over so much of northern Europe, rest on boulder-clay. Among these accumulations are the sheets of coarse, well-rounded gravel (plateau-gravel), which, with no recognisable relation to the present contours of the ground, are spread over the plains and low plateaux, and fill up many valleys. These gravels rest sometimes on boulder-clay, sometimes on solid rock, and are older than the valley alluvia. They have evidently not been formed by any ordinary river-action, nor is it easy to see how the sea can have been concerned in their formation. They are well developed in Norfolk and adjacent tracts of the south-east of England, where they consist mainly of well-rounded flints (cannon-shot gravel).

Still more remarkable are the accumulations of sand and gravel to which the name of "Kame group" has been given. Covering the lower ground in a sporadic manner, often tolerably thick on the plains, these deposits rise up to heights of 1000 feet or more. In some places, they cannot be satisfactorily separated from the sands and gravels associated with the boulder-clay, in others they seem to merge into the sandy deposits of the raised beaches, while in hilly tracts it is sometimes hard to distinguish between them and true moraine-stuff. Their most remarkable mode of occurrence is when they assume the form of mounds and ridges, which run across valleys and plains, along hillsides, and even over water-sheds. Frequently these ridges coalesce so as to enclose basin-shaped hollows, which are often occupied by tarns. Many of the most marked ridges are not more than 50 or 60 feet in diameter, sloping up to the crest, which may be 20 or 30 feet above the plain. A single ridge may occasionally be traced in a slightly sinuous course for many miles, as in the case of the famous mound which runs across the centre of Ireland. These ridges, known in Scotland as Kames, in Ireland as Eskers, and in Scandinavia as Ösar, consist sometimes of coarse gravel or earthy detritus, but more usually of clean, well-stratified sand and gravel, the stratification towards the surface corresponding with the external slopes of the ground, in such a manner as to prove that the ridges are usually original forms of deposit, rather than the result of the irregular erosion of a general bed of sand and gravel. Some writers have compared these features to the submarine banks formed in the pathway of tidal currents near the shore. But they appear rather to be of terrestrial origin, due in some way to the melting of the great snow-fields and glaciers, and the consequent discharge of large quantities of water over the country. But no very satisfactory explanation of their mode of formation has yet been given.

Over the tracts from which the ice-sheet retired, lakes are usually scattered in large numbers. Some of these lie in ice-worn basins of rock. Where the detritus has been strewn thickly over the ground, however, they rest in hollows of the clay, earth, sand, or gravel. The origin of these depressions in the drifts cannot be found in any denuding operation since the ice left. They are obviously original features of the surface, dating back to the time when the various drifts were laid down. In some cases they may be due to irregular deposition of the detritus, as where successive moraines are thrown across a valley. The small pools may sometimes have been originated by the melting of portions of ice which had become detached from the main mass, and were surrounded by or buried under detritus. Many small rock-basins may have had their place and form determined by that prolonged deep subaerial rotting already referred to, while others may be referable to underground movements. But the glaciers, in smoothing and polishing the rocks, wore them down unequally, hollowing them into rock-basins, leaving them in prominent smoothed domes, and carrying the same characteristic sculpture over all the durable rocks exposed in the areas of intenser glaciation.

The uprise of the land in Scandinavia and Britain took place interruptedly. During its progress it was marked by long pauses when the level remained unchanged, when the waves and floating ice cut ledges along the sea-margin, and when sand and gravel were accumulated below high-water mark in sheltered parts of the coast-line. These platforms of erosion and deposit (raised beaches) form conspicuous features at successive heights above the present level of the sea (p. 285). The coast of Scotland is fringed with a succession of them (Fig. 457). Those below the level of 100 feet above the sea are often remarkably fresh. The 100-feet terrace forms a wide plateau in the estuary of the Forth, and the 50-feet terrace is as conspicuous in that of the Clyde. In Scandinavia, especially in the northern parts of Norway, the successive pauses in the last uprise of the land are impressively revealed by long lines of terraces which wind around the hill-slopes that encircle the fjords (p. 287).

The records of the closing ages of the long and varied Glacial Period merge insensibly into those of later geological times. It is obvious that besides the effect of a general change of climate operating over the whole of the northern hemisphere, we must remember the influence which the natural features of different countries had upon the climate. From the plains, the ice and snow would retire sooner than from the hills. In fact, we may regard some parts of Europe as still retaining the conditions of the Glacial Period, though in diminished intensity, the present glaciers of the Alps being, as above remarked, the representatives in continuous succession of the vaster sheets that once descended into the lowlands on all sides from that central elevated region. And even where the ice has long since disappeared, there remain, in the living plants and animals of the higher and colder uplands, witnesses to the former severity of the climate. As that severity lessened, the Arctic vegetation, that hitherto had peopled all the lower grounds of central and western Europe, was driven up into the hills before the advance of plants loving a milder temperature, which had doubtless been natives of Europe before the period of great cold, and which were now enabled to reoccupy the sites whence they had been banished. On the higher mountains, where the climate is still not wholly uncongenial for them, and likewise here and there at lower levels, colonies of the once general Arctic flora still survive. The Arctic animals have also been mostly driven away to their northern homes, or have become wholly extinct. But the remains of the Arctic plants and to some extent also of the animals occur in the lacustrine clays, peat-mosses and other deposits of the glacial series, even down into the heart of Europe.

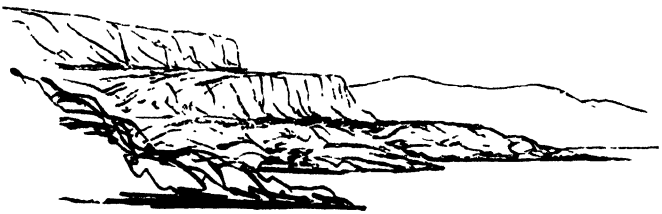

Fig. 457.—Terraces of erosion, marking ancient shore-lines. South coast of Island of Mull.

It has been forcibly pointed out by Mr. Wallace that the present mammalian fauna of the globe presents everywhere a striking contrast to the extraordinary variety and great size of the mammals of the Tertiary periods. "We live," he says, "in a zoologically impoverished world, from which all the largest, and fiercest, and strangest forms have recently disappeared."[1] He connects this remarkable reduction with the refrigeration of climate during the Glacial Period. The change, to whatever cause it may be assigned, is certainly remarkably persistent in the Old World and in the New, and not merely in the temperate and northern regions, but even as far south as the southern slopes of the Himalaya Mountains.

§ 2. Local Development.

Britain.[2]—Though the generalised succession of phenomena above given is usually observable, some variety is traceable in the evidence in different parts of the British area. In Scotland, where the ground is generally more elevated, and where snow and ice were most abundant, the phenomena of glaciation reached their maximum development. In the high grounds of England, Wales, and Ireland there was likewise extensive accumulation of ice. The ice-worn rocks of the low grounds are usually covered with boulder-clay, which in Scotland is interstratified with beds of sand, fine clay, and peat, but has never yielded any marine organisms except near the coast, where they are sometimes common, and in one locality in Lanarkshire. In England, marine shells, usually fragmentary, occur in the boulder-clays both in the eastern and western counties. The ice-sheet no doubt passed over some parts of the sea-bottom, and ground up the shell-banks that happened to lie in its way, as has happened, for example, in Caithness, Holderness, and East Anglia, where the shells in the boulder-clay are fragmentary, and sometimes ice-striated. The "Bridlington Crag" of Yorkshire, according to Messrs. Sorby, Lamplugh, and Reid, is a large fragment torn from a submarine shell-clay, and imbedded in the boulder-clay.[3] With the exception of such marine enclosures, the organic contents as well as the physical characters of the Scottish Till point to terrestrial conditions of deposit under the ice-sheet.

The depth, extent, and movements of the great ice-sheet which covered Britain have already been referred to. The proofs of the former presence of the ice are scattered abundantly over the country north of a line drawn from the Bristol Channel to the estuary of the Thames. South of that line the ground is free from boulder-clay, though various deposits, possibly of contemporary date, serve to indicate that though not buried under ice this southern fringe of England had its own glacial conditions.[4] Among these is the "Coombe-rock" of Sussex—a mass of unstratified rubbish which has been referred by Mr. C. Reid to the action of heavy summer rains at a time when the ground a little below the surface was permanently frozen. In the glaciated tract one of the most striking features in showing the Greenland-like massiveness of the ice-sheet is furnished by the south of Ireland, where the hills of Cork and Kerry have been ground smooth and striated down to the sea, and even under sea-level, detached islets appearing as well ice-rounded *roches moutonnées.* There can be no doubt from this evidence that even in the south of Ireland the ice-sheet continued to be so massive that it went out to sea as a great wall of ice, probably breaking off there in icebergs.

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[1] 'Geographical Distribution of Animals,' i. p. 150. Consult also Asa Gray, *Nature*, xix. p. 327 (363).

[2] Besides the general works and papers already cited, the following special papers in the *Quarterly Journal of the Geological Society* may be consulted: *Wales*, Mackintosh, 1882, p. 184; I. W. E. David, 1883, p. 39. *N. W. England*, Mackintosh, 1879, p. 425, 1880, p. 178; T. M. Reade, 1874, p. 27, 1883, p. 83; A. Strahan, 1886, p. 369. *S.E. England*, Searles V. Wood jun. 1880, p. 457, 1882, p. 667; A. J. Jukes-Browne, 1879, p. 397, 1883, p. 596; Rowe, 1887, p. 351. *Scotland* (Long Island), J. Geikie, xxix. (1873); xxxiv. (1878); (Shetlands) Peach and Horne, 1879, p. 778; (Orkneys) 1880, p. 648; (Aberdeenshire) T. F. Jamieson, 1882, pp. 145, 160. The student will find a useful digest of the literature for England up to 1887 in Mr. H. B. Woodward's 'Geology of England and Wales.' The *Memoirs of the Geological Survey* will be found to contain much local detail on this subject.

[3] Lamplugh, *Quart. Journ. Geol. Soc.* xl. (1884) p. 312. C. Reid, 'Geology of Holderness' in *Mem. Geol. Survey*.

[4] C. Reid, *Quart. Journ. Geol. Soc.* xliii. (1887) p. 364.

The records of the submersion of Britain are probably very incomplete. If we rely only on the evidence of untransported marine shells, we obtain the lowest limit of depression. But, as above remarked, the mere presence of marine shells cannot always be accepted as conclusive. Again, the renewed ice and snow, after re-elevation, may well have destroyed most of the shell-beds, and their destruction would be most complete where the snow-fields and glaciers were most extensive. • Beds of sand and gravel with recent shells have been observed on Moel Tryfaen, in North Wales, at a height of 1350 feet, but the shells are broken and show such a curious commingling of species as to indicate that they are probably not really in place. In Cheshire marine shells occur at 1200 feet. In Scotland they have been obtained at 524 feet in the boulder-clay at the Lanarkshire locality already referred to ; but the layer containing them may have been transported by the ice-sheet. Subsequent elevation of the land has brought up within tide-marks some of the clays deposited over the sea-floor during the time of the submergence. In the Clyde basin and in some of the western fjords, these clays (Clyde Beds) are full of shells. Comparing the species with those of the adjacent seas, we find them to be more boreal in character ; nearly the whole of the species still live in Scottish seas, though a few are extremely rare. Some of the more characteristic northern shells in these deposits are *Pecten islandicus, Tellina lata* (*T. calcarea*), *Leda truncata, L. lanceolata, Yoldia arctica, Saxicava rugosa, Panopæa norvegica, Trophon scalariformis* (*T. clathratus*), and *Natica clausa* (Fig. 458).

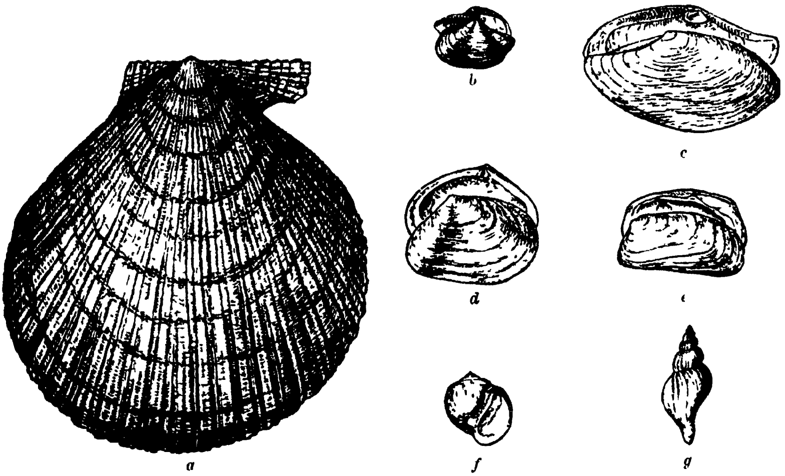

Fig. 458.—Group of Shells from the Scottish Glacial

a, Pecten islandicus, Mull. (½) ; *b*, Leda truncata, Brown (½) ; *c*, Leda lanceolata, Sow. (½) ; *d*, Tellina lata, Gmelin (T. calcarea, Wahl.) (½) ; *e*, Saxicava rugosa, Pennant (½) ; *f*, Natica clausa, Brod. and Sow. (½) ; *g*, Trophon scalariformis, Gould (T. clathratus) (½).

Of the later stages of the Glacial Period, the records are much the same all over Britain, allowance being made for the greater cold and longer lingering of the glaciers in the north than in the south, and among the hills than on the plains.

In Scotland the following may be taken as the average succession of glacial phenomena in descending order:—

Last traces of glaciers, small moraines at the foot of corries among the higher mountain groups. The glaciers, no doubt, lingered longest among the higher mountains of the north-west (Highlands, Galloway, Lead Hills, Hartfell and Loch Skene, Arran, Mull, Skye, Harris, Orkney, Shetland).

Marine terraces (50 feet and higher). Clay-beds of the Arctic sea-bottom (Clyde Beds) containing northern mollusks. The marine terraces prove a submergence of at least 100 feet beneath the present level of the land; how much beyond that limit the submergence reached has still to be determined.

Large moraines, showing that glaciers descended to the line of the present sea-level in the north-west of Scotland. Some of the moraines rest upon the 50-feet marine terrace.

Erratic blocks, chiefly transported by the first ice-sheet, but partly also by the later glaciers, and partly by floating ice during the period of submergence.

Sands and gravels—Kame or Esker series, sometimes containing terrestrial organisms, sometimes marine shells.

Upper boulder-clay—rudely stratified clays with sands and gravels.

Till or lower boulder-clay (bottom moraine of the ice-sheet)—a stiff stony unstratified clay, varying up to 100 feet or more in thickness. Bands of fine sand, finely laminated clays, layers of peat and terrestrial vegetation, with bones of mammoth and reindeer, also in some places fragmentary or entire Arctic and boreal marine shells, occur either in the till or between it and the upper boulder-clay. Till spreads over the lower grounds, often taking the form of parallel ridges or drums.

Ice-worn rock surfaces.

Over a great part of England and Ireland the drift deposits are capable of subdivision as follows:—

4. Moraines (North Wales, Lake District, &c.) and raised beaches.
3. Upper boulder-clay—a stiff stony clay or loam with ice-worn stones and intercalations of sand, gravel, or silt. It occasionally contains marine shells. It possibly does not come south of the Wash.
2. Middle sands and gravels, containing marine shells. At Macclesfield (1200 feet above the sea) there have been found *Cytherea chione*, *Cardium rusticum*, *Arca lactea*, *Tellina balthica*, *Cyprina islandica*, *Astarte borealis*, and other shells now living in the seas around Britain, but indicating perhaps by their grouping a rather colder climate than the present. *Corbicula fluminalis* abounds in some gravels which underlie the upper boulder-clay. South of the Wash it is found in similar deposits overlying the lower or "chalky boulder-clay." In Ireland marine shells of living British species occur at heights of 1300 feet above the sea. But, for the reason already assigned, the submergence may not have been nearly so great as these high-lying shelly deposits might be supposed to indicate.
1. Lower boulder-clay—a stiff clayey deposit stuck full of ice-worn blocks, and equivalent to the till of Scotland. On the east coast of England (Holderness, Lincoln and Norfolk) it contains fragments of Scandinavian rocks; in particular, gneiss, mica-schist, quartzite, granite, syenite, rhombenporphyr; also pieces of red and black flint, probably from Denmark, and of Carboniferous limestone and sandstone, which have doubtless travelled from the north. Along the Norfolk cliffs it presents stratified intercalations of gravel and sand, which have been extraordinarily contorted. As in Scotland, the true lower boulder-clay in the north of England and Ireland is often arranged in parallel ridges or drums in the prevalent line of ice-movement. As above mentioned, the "crag" of Bridlington, Yorkshire, is probably a fragment of an old marine glacial shell-bearing clay, torn up and imbedded in the boulder-clay of the first ice-sheet. Its shells are strikingly Arctic.

The southern limit of the ice has been already mentioned (p. 1027). No "terminal

> moraine" has been observed, the ground to the south of the ice-limit being free from glaciation, though erratic blocks, probably brought by drift-ice, are found on the Sussex coast. The Coombe-rock has been already referred to (p. 1042). Deep superficial accumulations of rotted rock occur where the rock has decomposed *in situ* in the southern non-glaciated region, as may be well seen over the Palæozoic slates and granites of Devon and Cornwall. In the non-glaciated chalk districts, a thick cover of flints and red earth partly represents the insoluble parts of the chalk that remain after prolonged subaerial decay, but from the frequent presence of fragments of quartz, which does not occur in the chalk, this mantle of "clay with flints" seems to indicate also a certain amount of transport, though the agent by which this was effected is not obvious. The high moorlands of eastern Yorkshire appear to have risen as an insular tract above the ice-sheet; for the boulder-clay advances up the valleys that indent the northern face of the Jurassic table-land, but ceases about a height of 800 feet, and the table-land itself is entirely free of drift, but its rocks are much decayed at the surface.

Scandinavia.[1]—The order of Pleistocene phenomena is generally the same here as in Britain. The surface of the country has been everywhere intensely glaciated, and, as already stated, the ice-striæ and transported stones show that the great ice-sheet probably exceeded 3000 feet in thickness, for the hills are ice-worn for more than 5000 feet above sea-level, and that moving outwards from the axis of the peninsula it passed down the western fjords into the Atlantic, and southwards and south-eastwards into the Baltic. The subsequent partial submergence of the country is proved by numerous shell-bearing clays. The fossils in the higher littoral shell-beds indicate a more Arctic climate; they include, as in the Scottish glacial clays, great numbers of thick-shelled varieties of *Mya truncata* and *Saxicava rugosa;* also *Balanus porcatus, B. crenatus, Mytilus edulis, Pecten islandicus, Buccinum grœnlandicum, Trophon scalariformis,* (*T. clathratus*), *Natica clausa.* The clays of deeper water contain *Leda lanceolata, Yoldia arctica, Y. intermedia, Y. pygmæa, Dentalium abyssorum,* &c. The fossiliferous deposits of lower levels point to a climate more nearly approaching the present, for the more thoroughly Arctic species disappear, and the thick-shelled varieties of *Mya* and *Saxicava* pass into the usual thin-shelled kinds. The remarkable terraces that fringe the coast of Norway from the southern or Christiania region to the North Cape mark pauses in the re-elevation of the land (Fig. 78). The eastern plains of Sweden and the lower grounds of southern Norway are covered with great accumulations of sand and gravel (osar) like the kames of Scotland and the eskers of Ireland.

Germany.[2]—Since the year 1878 an active exploration of the earlier memorials of the glacial period has been carried on in northern Germany, with the result of bringing out more clearly the evidence for the prolongation of the Scandinavian and Finland ice across the Baltic and the plains of Germany even into Saxony. The limits reached by the ice are approximately fixed by the line to which northern erratics can be traced. Beneath the oldest members of the glacial drifts, deposits are found in a fragmentary condition containing shells now living only in southern Europe, such as *Paludina diluviana* and *Corbicula fluminalis.* Above the glaciated rocks comes a stiff, unstratified clay, with ice-striated blocks of northern origin—the till or boulder-clay (Geschiebelehm, Blocklehm). Two distinct boulder-clays have now been recognised—the older or till separated by interglacial deposits from the newer. Terminal moraines marking the limits of the ice-sheet have been found in the form of ramparts of Scandinavian blocks and gravel, which have been traced for many miles along the coast-line and across the plains of northern Germany.[1] The sources of the various ice-streams which united to form the great ice-sheet that crept over the Germanic plain are well shown by a study of the stones in the moraine material. The Scandinavian rocks are found towards the west and the Finnish towards the east of the glaciated area. Among the intercalated materials that separate the two boulder-clays are layers of peat, with remains of pine, fir, aspen, willow, white birch, hazel, hornbeam, poplar, holly, oak, juniper, ilex, and various water-plants, in particular a water-lily no longer living in Europe. With this vegetation are associated remains of *Elephas antiquus*, mammoth, rhinoceros, elk, megaceros, reindeer, musk-ox, bison, bear, &c. Some of the interglacial deposits are of marine origin on the lower grounds bordering the Baltic, for they contain *Cyprina islandica*, *Yoldia arctica*, *Tellina solidula*, &c. Among the youngest glacial, and probably in part interglacial, deposits are the upper sands and gravels (Geschiebedecksand), which spread over wide areas of the Germanic plain, partly as a more or less uniform but discontinuous sheet, and partly as irregular hillocks and ridges strewn with erratic blocks, and enclosing pools of water and peat-bogs. These mounds and ridges, with their accompanying sheets of water, form a conspicuous feature of the low tract of country from Schleswig Holstein eastwards to the Vistula.

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[1] See G. de Geer, *Zeitsch. Deutsch. Geol. Ges.* xxxvii. (1885) p. 177.

[2] There is now an ample though recent literature devoted to the glacial phenomena of Germany. The volumes of the *Zeitsch. Deutsch. Geol. Gesellschaft* for 1879 and subsequent years contain papers by G. Berendt, H. Credner, A. Helland, A. Penck, R. Richter, F. Noetling, F. Wahnschaffe, F. E. Geinitz, F. Schmidt, &c. See also the *Jahrb. Preuss. Geol. Landesanstalt* for 1880 and following years; the Maps and Explanations of the same Survey for the neighbourhood of Berlin (27 sheets) and the memoirs of the Geological Survey of Saxony.

In some of the mountain groups of Germany there is evidence that probably at the height of the Ice Age glaciers existed. Reference has already been made to the moraine mounds of the Vosges[2] and Black Forest,[3] and to the fact that the glaciers of the western hill-groups were more extensive than those to the east. In the Carpathian range, a series of moraines, sometimes enclosing lakes, is distributed in the valleys that radiate from the Hohe Tatra.[4] On both sides of the Riesengebirge, moraines occur. At the sources of the Lomnitz, on the southern side, they enclose two lakes at the foot of high recesses and cliffs.[5] No certain traces of glaciers appear to have been met with in the eastern part of the Sudeten range, nor in the Erzgebirge or Thuringerwald. Farther north, in the Harz, mounds of detritus which resemble moraines have been referred by Kayser to glacier-action.[6]

France.—As France lay to the south of the northern ice-sheet, the true till or boulder-clay is there absent, as it is for the same reason from the south of England. It is consequently difficult to decide which superficial accumulations are really contemporary with those termed glacial farther north, and which ought to be grouped as of later date. The ordinary sedimentation in the non-glaciated area not having been interrupted by the invasion of the ice-sheet, deposits of pre-glacial, glacial, and post-glacial time naturally pass insensibly into each other. The older Pleistocene deposits (perhaps interglacial) consist of fluviatile gravels and clays which, in their composition, belong to the drainage systems in which they occur. There is generally no evidence of transport from a great distance, though, in the Champ de Mars at Paris, blocks of sandstone and conglomerate nearly a yard long sometimes occur, as well as small pieces of the granulite of the Morvan. Erratics at Calais and on the coast of Brittany may also have been carried a long way.[7] The rivers, however, were probably much larger during some part of the Pleistocene period than they now are, and the transport of their stones may have been sometimes effected by floating ice. They have left their ancient platforms of alluvium in successive terraces high above the present watercourses. Each terrace consists generally of the following succession of deposits in ascending order: (1) A lower gravel (*gravier de fond*), the pebbles of which are coarsest towards the bottom and are interstratified with layers of sand, sometimes inclined and contorted. (2) Grey sandy loam (*sable gras*). (3) The foregoing strata are covered by yellow calcareous loess (p. 332), or with an overlying dark brown loam or brick-earth. The upper exposed parts of the gravels and sands are commonly well oxidised, and present a yellowish-brown or deep reddish-brown tint, while the lower portions remain more or less grey. Hence the old names *diluvium gris* and *diluvium rouge.* The gravels and brick-earths have yielded terrestrial and fresh-water shells, most of which are of still living species, and numerous mammalian bones, among which are *Rhinoceros antiquitatis* (*tichorhinus*), *R. etruscus*, *R. leptorhinus*, *Hippopotamus amphibius*, *Elephas antiquus*, *E. primigenius*, wild boar, stag, roe, ibex, Canadian elk, musk-sheep, urus, beaver, cave-bear, wolf, fox, cave-hyæna, and cave-lion. Palæolithic implements found in the same deposits show that man was a contemporary of these animals (see p. 1057).[1]

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[1] G. Berendt, *Jahrb. Preuss. Geol. Landesanst.* 1888, p. 110 ; K. Keilhack, *op. cit.* 1889, p. 149.

[2] H. Hogard, 'Terrain erratique des Vosges,' 1851.

[3] J. Partsch, 'Gletscher der Vorzeit,' 1882, p. 115.

[4] *Ibid.* p. 9.

[5] *Ibid.* p. 55.

[6] Lossen and Kayser, *Zeitsch. Deutsch. Geol. Ges.* xxxiii. (1881).

[7] Ch. Velain, *Bull. Soc. Géol. France*, xiv. (1886) p. 569.

It is in the centre and east of France that the most unequivocal signs of the ice of the Glacial Period are to be met with. The mountain groups of Auvergne, which even now show deep rifts of snow in summer, had their glaciers whereby moraine heaps and large blocks of rock were strewn over the valleys; not only so, but there is evidence in that region of a retreat and redescent of the ice, for above the older moraines lie interglacial deposits containing abundant remains of land-plants with bones of *Elephas meridionalis*, *Rhinoceros leptorhinus*, &c., the whole being covered by newer moraines.[2]

The much lower grounds of the Lyonnais and Beaujolais (rising to more than 3000 feet) likewise supported independent snow-fields.[3] The glacier of the Rhone and its tributaries at the time of the maximum glaciation was so gigantic as to fill up the hollow of the Lake of Geneva and the vast plain between the Bernese Oberland and the Jura. It crossed the Jura and advanced to near Besançon. It swept down the valley below Geneva, and then, joined by its tributaries, spread out over the lower hills and plains until the whole region from Bourg to Grenoble was buried under ice. The evidence of this great extension is furnished by rock-striæ, transported blocks and moraine stuff.[4]

Belgium.—The Quaternary deposits of this country, like those of northern France, belong to a former condition of the present river-basins. In the higher tracts, they are confined to the valleys, but over the plains they spread as more or less continuous sheets. Thus, in the valley of the Meuse, the gravel-terraces of older diluvium on either side bear witness only to transport within the drainage-basin of the river, though fragments of the rocks of the far Vosges may be detected in them. The gravels are stratified, and are generally accompanied by an upper sandy clay. In middle Belgium, the lower diluvial gravels are covered by a yellow loam (Hesbayan), probably a continuation of the German loess, with numerous terrestrial shells (*Succinea oblonga*, *Pupa muscorum*, *Helix hispida*). In lower Belgium, this loam is replaced by the Campinian sands, which have been observed lying upon it. The Belgian caverns and some parts of the diluvium have yielded a large number of mammalian remains, among which there is the same commingling of types from cold and from warm latitudes so observable in the Pleistocene beds of England and France. Thus the Arctic reindeer and glutton are found with the Alpine chamois and marmot, and with the lion and grizzly bear.

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[1] A detailed study of the Quaternary deposits of the north of France has been made by J. Ladrière, who divides them into three stages, each marked off by a gravelly layer at the base and terminating above in a loam with terrestrial vegetation and fresh-water and terrestrial shells. The lowest is the assise with *Elephas primigenius* and *Rhinoceros tichorhinus*. *Ann. Soc. Géol. Nord*, xviii. (1890), p. 93.

[2] Julien, 'Des Phénomènes glaciaires dans le Plateau central de la France,' 1869. Rames, *Bull. Soc. Géol. France*, 1884.

[3] Falsan and Chantre, 'Anciens Glaciers,' ii. p. 384.

[4] Falsan and Chantre, *op. cit.*

The **Alps.**[1]—Reference has already been made to the vast extension of the Alpine glaciers during the Ice Age. Evidence of this extension is to be seen both among the mountains and far out into the surrounding regions. On the sides of the great valleys, ice-striated surfaces and transported blocks are found at such heights as to show that the ice must have been in some places 3000 or 4000 feet thicker than it now is. The glacier of the Aar, for instance, which was a comparatively short one, being turned aside by and merging into the large stream of the Rhone glacier near Berne, attained such dimensions as not only to fill up the valley now occupied by the Lakes of Thun and Brienz, but to override the surrounding hills. The marks made by it are found at a height of 930 metres above the valley, which with 305 metres for the depth of Lake Brienz gives a depth of at least 1235 metres or 4000 feet of ice moving down that valley. Judging from the evidence of the heights of the stranded blocks, the slope of this glacier varied from 45 in 1000 in its upper parts to not more than 2 in 1000 towards its termination.[2] From the variation in the direction of the striæ, as well as in the distribution of the transported blocks, there can be little doubt that the Alpine glaciers varied from time to time in relative dimensions, so that there was a kind of struggle between them, one pushing aside another, and again being pushed aside in its turn.

Turning to the regions beyond the mountains, we find that proofs of glaciation reach to almost incredible distances. The Rhone glacier has already been referred to as overwhelming the mountainous and hilly intervening country, and throwing down its moraines with blocks of the characteristic rocks of the Valais where Lyons now stands, that is, 170 miles in direct distance from where the present glacier ends. The same ice-sheet, swelled from the northern side of the Bernese Oberland, overflowed the lower ridges of the Jura, streaming through the transverse valleys, even as far as Ornans near Besançon. Turning north-eastward, it filled up the great valley of Switzerland, and, swollen by the tributary glaciers of the Aar, the Reuss, and the Linth, joined the vast stream of the Rhine glacier above Basle. This enormous *mer de glace* poured over the Black Forest and down the valley of the Danube at least as far as Sigmaringen, where blocks of the rocks of the Grisons occur. Eastward it was joined by the great glacier that descended from the Swabian and Bavarian Alps, and of which the moraine-heaps are strewn over the lowlands as far as Munich. The Tyrolese and Carinthian Alps were likewise buried under an icy covering which sent a huge glacier eastwards down the valley of the Drau. On the south side of the Alps, the glaciers advanced for some way out into the plains of Lombardy, where they threw down enormous moraines, which sometimes reach a height of more than 2000 feet (Ivrea). These vast accumulations, to which there is no parallel elsewhere in Europe, rise into conspicuous hills and crescent-shaped ridges round the lower ends of the upper Italian lakes. At some of these localities the moraine stuff rests on marine Pliocene beds. It is possible that the glaciers actually reached the sea-level.[1] There appears to be no doubt, at least, that they descended to a lower level on that side than on the northern side of the Alps.

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[1] Besides the works of Falsan and Chantre, Penck and Partsch, cited on p. 1024, the student may consult Morlot, *Bib. Univ.* 1855; *Bull. Soc. Vaud. Sci. Nat.* 1858, 1860; Heer, 'Urwelt der Schweiz'; the map of the ancient glaciers of the north side of the Swiss Alps, published in four sheets by A. Favre, Geneva, 1884; C. W. Gümbel, *Sitzb. Akad. Wien*, 1872; R. Lepsius, 'Das westliche Süd-Tirol,' Berlin, 1878; A. Heim, 'Handbuch der Gletscherkunde,' 1885; Baltzer, *Mittheil. Naturf. Ges.* Berne, 1887; Renevier, *Bull. Soc. Helv.* 1887; A. Böhm, *Jahrb. k. k. Geol. Reichsanst.* xxxv. (1885) p. 429.

[2] A. Favre, *Arch. Ann. Sci. Phys. Nat. Genève*, xii. 1884.

By tracing the distribution of the transported blocks, the movements of the ancient glaciers can be satisfactorily followed. These blocks are not dispersed at random over the glaciated area. Each glacier carried the blocks of its own basin, and, where these are of a peculiar kind, they serve as an excellent guide in following the march of the ice. Not only were the blocks in each drainage area kept separate from those of adjoining basins, but those on the left sides of the valleys do not, except along the junction lines, mingle with those of the right sides. As a rule, the blocks lie along the slopes of the valleys rather than on the bottoms, and are often disposed there in groups or lines. In the Arve valley, near Sallanches, for example, a zone comprising several thousand granitic boulders runs for a distance of more than three miles. The blocks of Monthey have long been famous. On the flanks of the Jura near Solothurn, the boulders of Riedholz, stranded there by the ancient Rhone glacier, still number 228, though they have been reduced by the quarrying operations now happily interdicted (see Figs. 151, 152, 153).[2]

That the Ice Age in the Alps, as in northern Europe, was interrupted by at least one warmer interglacial period, when the ice retreating from the valleys allowed an abundant vegetation to flourish there, is shown by the lignites of Durnten (Canton Zurich), Utznach (St. Gall), Hotting (near Innspruck), and several other places. These deposits can here and there be seen to overlie ancient moraine stuff; they are interstratified with fluviatile gravels and sands, which again are surmounted with scattered erratic blocks belonging to a later period of glaciation. Among these interglacial vegetable accumulations Heer recognised several pines or firs (*Pinus abies*, *P. sylvestris*, *P. montana*), larch, yew, oak, sycamore, hazel, mosses, bog-bean, bulrush, raspberry, and *Galium palustre*, as well as bog-mosses, all still growing in the surrounding country. With the plants there occur the remains of *Elephas*, *Rhinoceros etruscus*, *Bos taurus*, var. *primigenius* or urus, red-deer, cave-bear, likewise traces of fresh-water shells and insects, chiefly elytra of beetles.

The succession of main events in the history of the Ice Age in Switzerland is thus tabulated:[3]—

Post-glacial. Ancient lacustrine terraces (150 feet above present level of Lake of Geneva), deltas, and river gravels with *Limnæa stagnalis*, and other fresh-water shells, bones of mammoth (?).
Second extension of the glaciers. Erratic blocks and terminal moraines of Zurich, Baldegg, Sempach, Berne, with an Arctic flora and fauna.
Interglacial beds. Gravels, lignites, and clays of Utznach, Durnten, &c., covered by the moraine stuff of the second glaciation and overlying the oldest glacial deposits—*Elephas antiquus*, *Rhinoceros leptorhinus*.
First glaciation. Striated blocks found under the interglacial beds.

Russia.—A vast extent of Russia was buried under the first great ice-sheet, the southward limits of which across the country have already been stated (p. 1027). There appears to be evidence that the second advance of the ice not only affected the western lowlands that were covered by the Baltic glacier, but even the centre of the country. Recently proofs have been obtained of an interglacial period in central Russia marked by lacustrine deposits intercalated between glacial clays. They have yielded an abundant

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[1] The surface of the Lago di Garda, round the lower end of which glacier moraines extend, is little more than 200 feet above the sea-level.

[2] Favre, *Arch. Sci. Phys. Nat. Genève*, xii. (1884) p. 399. Penck ('Vergletscherung der Deutschen Alpen') believes that he can trace evidence of at least three distinct periods of glaciation in the Alps.

[3] Heer, 'Urwelt der Schweiz.'

flora, including alder, birch, hazel, willow, fir, water-lilies, and remains of mammoth, &c.[1]

North America.[2]—*The general succession of geological change in Post-Tertiary time appears to have been broadly the same all over the northern hemisphere.* In North America, as in Europe, there is a glaciated and non-glaciated area; but the line of demarcation between them has been much more clearly traced on the western side of the Atlantic. The glaciated area extending over Canada and the north-eastern States presents the same characteristic features as in the Old World. The rocks, where they could receive and retain the ice-markings, are well smoothed and striated. The direction of the striæ is generally southward, varying to south-east and south-west according to the form of the ground. The great thickness of the ice-sheet is strikingly shown by the height to which some of the higher elevations are polished and striated. Thus the Catskill Mountains, rising from the broad plain of the Hudson, have been ground smooth and striated up to near their summits, or about 3000 feet, so that the ice must have been of even greater thickness than that. The White Mountains are ice-worn even at a height of 5500 feet. G. M. Dawson has found glaciated surfaces in British Columbia 7000 feet above the sea.[3]

As in Europe, the glacial deposits increase in thickness and variety from south to north, spreading across Canada, over a considerable area of the north-eastern States, and rising to a height of 5800 feet among the White Mountains. From the evidence of the rock-striæ and the dispersion of boulders, it appears that, though the glaciated region was buried under one deep continuous *mer de glace* like that of Greenland at the present time, moving steadily down from the north, there were considerable variations in the direction of motion, mainly, no doubt, owing to inequalities in the general slope of the ground underneath. Nothing, however, is more striking than the apparent indifference with which the ice streamed onward, undeflected even by considerable ridges and hills. The line of the southern margin of the ice can still be followed by tracing the limits to which the drift deposits extend southwards. From this evidence we learn that the ice-sheet ended off in a sinuous line, protruding in great tongues or promontories and retiring into deep and wide bays. In the eastern states, the southern limit of the glaciated region is marked by one of the most extraordinary glacial accumulations yet known, and to which in Europe there is no rival. It consists of a broad irregular band of confused heaps of drift, or more strictly of two such bands, which sometimes unite into one broad belt and sometimes separate wide enough to allow an interval of twenty or thirty miles between them, each being from one to six miles in breadth and rising several hundred feet above the surrounding country. The surface of these ridges presents a characteristic hummocky aspect, rising into cones, domes, and confluent ridges, and sinking into basin-shaped or other irregularly-formed depressions, like the kames or osar of Europe. The upper part of the material composing the ridges generally consists of assorted and stratified gravel and sand, the stratification being irregular and discordant, but inclined on the whole towards the south. Below these rearranged materials is a boulder-drift—a mixture of clay, sand, and gravel, with boulders of all sizes, up to blocks many tons in weight and often striated. Though sometimes indistinguishable from ordinary till, it presents as a rule a greater preponderance of stones than in typical till, but contains also fine stratified intercalations. A large proportion of the material of the ridges has been derived from rocks lying immediately to the north, and the nature of the ingredients constantly varies with the changing geological structure of the ground. There is also always present a greater or less amount of detritus representing rocks that lie along the line of drift-movement for 500 miles or more to the north. The band of drift-hills lies sometimes on an ascending, sometimes on a descending slope, crosses narrow mountain ridges and forms embankments across valleys, showing such a disregard of the topography as to prove that it cannot have been a shore-line, and has not been laid down with reference to the present drainage system of the land.[1]

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[1] N. Krischtafowitsch, *Bull. Soc. Imp. Nat. Moscou*, No. 4 (1890). On the glaciation of the Urals see Nikitin, *Neues Jahrb.* 1888, i. p. 172.

[2] See J. D. Whitney, "Climatic Changes of later Geological Times," *Mem. Mus. Compar. Zool. Harvard*, vol. vii. 1882; and papers by J. D. Dana, T. C. Chamberlin, R. D. Salisbury, W. Upham, George M. Dawson, H. Carvill Lewis, G. F. Wright, and others in *Amer. Journ. Sci.*, *American Geologist*, *Canadian Naturalist*, *Canadian Journal*, *Ann. Reports of U.S. Geol. Survey*, and *Canadian Geol. Survey*, *Second Geol. Surv. of Pennsylvania*. J. W. Dawson, 'Acadian Geology,' 1878; 'Handbook of Canadian Geology,' 1889; G. M. Dawson, *Trans. Roy. Soc. Canada*, viii. sect. iv. (1890) p. 25; G. F. Wright, 'Man and the Glacial Period,' 'The Ice Age in America.'

[3] *Geol. Mag.* 1889, p. 351; see also W. Upham, *Appalachia*, v. (1889) p. 291.

To this remarkable belt of prominent hummocky ground the name of "terminal moraine" has been given by the American geologists who have so successfully traced its distribution and investigated its structure. The conditions, however, under which the drift rampart in question was formed certainly differed widely from those that determine an ordinary terminal moraine. The constituent materials can hardly have travelled on the surface of the ice, but must rather have lain underneath it or have been pushed forward in front of it. But the mode of formation is a problem which has not yet been satisfactorily solved.

There seems good reason to believe that there are at least two "terminal moraines" belonging to two distinct and perhaps widely separated epochs in the Ice Age. The most southerly and therefore oldest of them begins on the Atlantic border off the south-eastern coast of Massachusetts, where it is partially submerged. Rising above the level of the sea in Nantucket Island, Martha's Vineyard, No Man's Island and Block Island, it is prolonged into Long Island, of which it forms the back-bone, and where it reaches heights of 200 to nearly 400 feet. A second or later and less prominent line of drift-hills runs along the north shore of Long Island, and is prolonged by Fisher's Island into the southern edge of the State of Rhode Island, whence, striking out again to sea, it forms the chain of the Elizabeth Islands, passes thence into the State of Massachusetts, and runs nearly east and west through the peninsula of Cape Cod. The distance between these two bands of hummocky ridge varies from five to thirty miles. From the western end of Long Island the moraine passes across Staaten Island and the northern part of New Jersey, enters Pennsylvania a little north of Easton, and follows a sinuous north-westerly course across that State and for some miles into the State of New York, where, forming a deep indentation, it wheels round in a south-westerly direction, re-enters Pennsylvania, and passes into Ohio. Throughout this long line, the moraine coincides with the southern limit of the drift and of rock-striation, though in western Pennsylvania, in front of the ridge, scattered northern boulders are found over a strip of ground which gradually increases south-westwards to a breadth of five miles.[2] Beyond central Ohio, however, the drift extends far to the south. Taking its limits as probably marking the extreme boundary of the ice-sheet (then at its largest), we find that it goes southwards, perhaps nearly as far as the junction of the Ohio with the Mississippi, sweeping westwards into Kansas, and then probably turning northwards through Nebraska and Dakota, but keeping to the west of the Missouri River.

The inner or second terminal moraine is well developed in the southern part of the State of New York, lying well to the north of the first moraine, and much more irregularly distributed. South-westwards the two series of ramparts unite at the sharp bend of the older ridge just mentioned, and continue as one into the centre of Ohio. This junction probably indicates that the southern edge of the ice at the time of the second moraine, though generally keeping to the north of its previous limit, reached its former extent in north-western Pennsylvania, and united its débris with that left at the time of the greatest extension of the ice-sheet. From the middle of Ohio, the younger moraine pursues an extraordinarily sinuous course. One of its most remarkable bends encloses the southern half of Lake Michigan, which was the bed of a great tongue of ice moving from the north. Immediately to the west of this loop there lies an extensive driftless area in Wisconsin and Minnesota. The course of the moraine bears distinct witness to the independent direction of flow of the united glaciers that constituted the great ice-sheet. It sweeps in vast indentations and promontories across Wisconsin, Minnesota, and Iowa, forming probably the most extensive moraine in the world, and strikes north-westward through Dakota for at least 400 miles into the British Possessions, where its further course has been partially traced. The known portion of the moraine thus extends with a wonderful persistence of character for 3000 miles, reaching across two-thirds of the breadth of the continent.[1]

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[1] H. C. Lewis, "Report on the Terminal Moraine," *Second Geol. Surv. Pennsylvania*, Z, 1884, p. 45, with Preface by J. P. Lesley.

[2] This strip of ground, called by the late Prof. H. C. Lewis the "fringe," widens out south-westwards, as stated above, to a breadth of five miles, in which, though there are no rock-striæ or drift, scattered northern boulders occur. *Op. cit.* p. 201.

In the non-glaciated regions evidence of the presence and influence of the ice-sheet is probably furnished by high alluvial terraces, which could not have been formed under the present conditions of drainage. From this kind of evidence it is believed that when the ice-sheet crossed the Ohio River near Cincinnati, it ponded back the drainage of the entire water-basin of East Kentucky, south-east Ohio, West Virginia, and western Pennsylvania, up to a height of perhaps 1000 feet, forming a lake at that level.[2] Similar indications of a lake, caused by an ice-dam ponding back the drainage, are found at the head of the Red River in Minnesota.[3] The largest sheet of fresh water which has left its records in that region has been called "Lake Agassiz." It occupied the basin of the Red River of the North and Lake Winnipeg. It is computed to have covered an area of 110,000 square miles, thus exceeding the total area of the five great existing lakes—Superior (31,200), Michigan (22,450), Huron with Georgian Bay (23,800), Erie (9960), Ontario (7240), which have a united area of 94,650 square miles.[4] Many other "glacial lakes," which no longer exist because their ice-barriers have disappeared, have been found scattered over Canada.[5]

The deposits left by the ice-sheet within the limits of the terminal moraines so resemble those of Europe that no special description of them is required. The lowest of them, resting on ice-worn rocks, is a stiff, unstratified boulder-drift or till, full of polished and striated stones. Occasional intercalations of sand and clay, which at Portland, in Maine, have yielded many existing species of marine organisms, and in some places land-plants and fresh-water shells, separate the lower from an upper boulder-clay, which is looser, and more gravelly and sandy than the older deposit, contains larger rough and angular blocks, and has acquired a yellow tint from the oxidising influence of surface waters. The boulders vary up to 10 feet (sometimes even 40 feet) in diameter, and have seldom travelled more than 20 miles. The boulder-clays over wide areas are distributed in lenticular hills or drums from a few hundred feet to a mile in length, from 25 to 200 feet high, and with a persistent smoothness of outline and rounded tops.[1] As in Europe, the longer axes of these drums is generally parallel with that of the striation of the underlying rocks.

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[1] T. C. Chamberlin, "Preliminary Paper on the Terminal Moraine," *Third Ann. Rep. U.S. Geol. Survey*, 1883. Every student of glacial geology ought to make himself familiar with this admirable summary. Consult also G. M. Dawson, 'Report on 49th Parallel'; F. Wahnschaffe, *Zeitsch. Deutsch. Geol. Ges.* 1892, p. 107; J. B. Tyrrell (*Bull. Geol. Soc. Amer.* i. (1890) p. 395) describes the terminal moraines in Manitoba and the adjacent territories of N.W. Canada.

[2] H. C. Lewis, "Report on the Terminal Moraine," cited on p. 1051.

[3] W. Upham, *Proc. Amer. Assoc.* xxxii. (1883) p. 214.

[4] For a full account of this vanished lake (now represented only by scattered sheets of water in the hollows of its basin), with its terraces, dunes, deltas, and other features, see W. Upham, *Rep. Geol. Surv. Canada*, vol. iv. for 1888-89.

[5] W. Upham, *Bull. Geol. Soc. Amer.* ii. (1891) p. 243.

At the height of the Ice Age there were large glaciers in the Rocky Mountains, of which the small glaciers found some years ago among the Wind River Mountains in Wyoming are some of the last lingering relics.[2] But though the ice filled up the valleys to a depth of 1600 feet or more, and transported vast quantities of detritus which now remains in prominent moraines and scattered boulders, it never advanced into the plateau of the prairie country to the east. Whether or not the glaciers at the north end of the Rocky Mountains merged into and were turned aside by the southward-moving ice-sheet has still to be ascertained. Even far to the west, the Sierra Nevada nourished an important group of glaciers.[3]

The loose deposits or drifts overlying the lower unstratified boulder-clay belong to the period of the melting of the great ice-sheets, when large bodies of water, discharged across the land, levelled down the heaps of detritus that had formed below or in the under part of the ice. This remodelled drift has been called the "Champlain group."[4] Lower portions are sometimes unstratified or very rudely stratified, while the upper parts are more or less perfectly stratified. Towards the eastern coasts, and along the valleys penetrating from the sea into the land, these stratified beds are of marine origin, and prove that during the Champlain period there was a depression of the eastern part of Canada and the United States beneath the sea, increasing in amount northwards from a few feet in the south of New England to more than 500 feet in Labrador. The marine accumulations are well developed in eastern Canada, where the drift-deposits show the following subdivisions :—

Post-glacial accumulations.
Saxicava sand and gravel, often with transported boulders (Upper Boulder deposits, St. Maurice and Sorel Sands). Shallow-water boreal fauna, *Saxicava rugosa*, bones of whales, &c.
Upper Leda clay (and probably "Saugeen clay" of inland); clay and sandy clay with numerous marine shells, which are the same as those now living in northern part of Gulf of St. Lawrence; also in some districts fresh-water shells and plants.[5]
Lower Leda clay, fine clay, often laminated, with a few large travelled boulders (probably equivalent to "Erie Clay" of inland; "Champlain Clay," Lower Shell-sand of Beauport); contains *Leda arctica*, *Tellina grœnlandica*; probably deposited in cold ice-laden water.
Boulder-clay or Till; in the Lower St. Lawrence region contains a few Arctic shells, but farther inland is unfossiliferous.
Peaty beds, marking pre-glacial land-surfaces.[6]

The Leda clays rise to a height of 600 feet above the sea. On the banks of the Ottawa, in Gloucester, they contain nodules which have been formed round organic bodies, particularly the fish *Mallotus villosus* or capeling of the Lower St. Lawrence. Sir J. W. Dawson also obtained numerous remains of terrestrial marsh-plants, grasses, carices, mosses, and algæ. This writer states that about 100 species of marine invertebrates have been obtained from the clays of the St. Lawrence valley. All except four or five species in the older part of the deposits are shells of the boreal or Arctic regions of the Atlantic; and about half are found also in the glacial clays of Britain. The great majority are now living in the Gulf of St. Lawrence and on neighbouring coasts, especially off Labrador.[1]

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[1] W. Upham, *Proc. Bost. Soc. Nat. Hist.* xxiv. (1889) p. 228. See on Till, W. O. Crosby, *op. cit.* xxv. (1890) p. 115.

[2] F. V. Hayden's Twelfth Report, *U.S. Geol. and Geog. Survey of the Territories.*

[3] J. Leconte, *Amer. Journ. Sci.* (3) ix. (1875) p. 126. See *Amer. Naturalist*, 1880, for a paper on the ancient glaciers of the Rocky Mountains.

[4] See J. D. Dana, *Amer. Journ. Sci.* x. (1875) p. 168, xxvi. (1883) xxvii. (1884); Winchell, *op. cit.* xi. (1876) p. 225.

[5] For a list of Canadian Pleistocene plants see D. P. Penhallow, *Bull. Geol. Soc. Amer.* i. (1890) p. 321.

[6] J. W. Dawson, Supplement to 'Acadian Geology,' 1878; *Canadian Naturalist*, vi. (1871); *Geol. Mag.* 1883, p. 111; *Bull. Geol. Soc. Amer.* i. (1890) p. 311.

Terraces of marine origin occur both on the coast and far inland. On the coast of Maine they appear at heights of 150 to 200 feet, round Lake Champlain at least as high as 300 feet, and at Montreal nearly 500 feet above the present level of the sea.[2] In the absence of organic remains, however, it is not always possible to distinguish between terraces of marine origin marking former sea-margins, and those left by the retirement of rivers and lakes. In the Bay of Fundy evidence has been cited by Dawson to prove subsidence, for he has observed there a submerged forest of pine and beech lying 25 feet below high-water mark.[3]

Inland, the stratified parts of the "Champlain group" have been accumulated on the sides of rivers, and present in great perfection the terrace character already (p. 396) described. The successive platforms or terraces mark the diminution of the streams. They may be connected also with an intermittent uprise of the land, and are thus analogous to sea-terraces or raised beaches. Each uplift that increased the declivity of the rivers would augment their rate of flow, and consequently their scour, so that they would be unable to reach their old flood-plains. Such evidences of diminution are almost universal among the valleys in the drift-covered parts of North America, as in the similar regions of Europe. Sometimes four or five platforms, the highest being 100 feet or more above the present level of the river, may be seen rising above each other, as in the well-known example of the Connecticut Valley.

The terraces are not, however, confined to river-valleys, but may be traced round many lakes. Thus, in the basin of Lake Huron, deposits of fine sand and clay containing fresh-water shells rise to a height of 40 feet or more above the present level of the water, and run back from the shore sometimes for 20 miles. Regular terraces, corresponding to former water-levels of the lake, run for miles along the shores at heights of 120, 150, and 200 feet. Shingle beaches and mounds or ridges, exactly like those now in course of formation along the exposed shores of Lake Huron, can be recognised at heights of 60, 70, and 100 feet. Unfossiliferous terraces occur abundantly on the margin of Lake Superior. At one point mentioned by Logan, no fewer than seven of these ancient beaches occur at intervals up to a height of 331 feet above the present level of the lake.[4] The great abundance of terraces of fluviatile, lacustrine, and marine origin led, as already stated, to the use of the term "Terrace epoch" to designate the time when these remarkable topographical features were produced. The cause of the former higher levels of the water is a difficult problem. In some cases it has doubtless arisen from dams formed by tongues of ice during the retreat of the ice-sheet.

India.—There is abundant evidence that at a late geological period glaciers descended from the southern slopes of the Himalaya Mountains to a height of less than 3000 feet above the present sea-level. Large moraines are found in many valleys of Sikkim and eastern Nepal between 7000 and 8000 feet, and even down to 5000 feet, above sea-level. In the western Himalayas perched blocks are found at 3000 feet, and in the Upper Punjaub very large erratics have been observed at still lower elevations.

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[1] Dawson, 'Acadian Geology,' p. 76.

[2] On terraces of Lake Ontario see *Amer. Journ. Sci.* (3) xxiv. p. 409.

[3] 'Acadian Geology,' p. 28.

[4] Logan, 'Geology of Canada,' p. 910. Consult also the paper by Gilbert on Lake Shores cited *ante*, p. 407.

No traces of glaciation have been detected in southern India. Besides the physical evidence of refrigeration, the present facies and distribution of the flora and fauna on the south side of the Himalaya chain suggest the influence of a former cold period.[1]

Australasia.—The present glaciers of the New Zealand Alps had a much greater extension at a recent geological period. According to Sir J. Haast they descended into the plains, and, on the west side of the island, probably advanced into the sea, for along that coast-line their moraines now reach the sea-margin ; huge erratics stand up among the waves, and the surf breaks far outside the shore-line, probably upon a seaward extension of the moraines.[2] Captain Hutton, however, points out that there is no evidence from the fauna of any general and serious refrigeration of the climate during this glacier period.[3] He believes that the principal part of the sub-tropical flora and fauna of New Zealand was introduced before the Miocene period, and has flourished ever since, and that any serious diminution of the temperature of the islands would have exterminated all but the more cold-loving species of plants and animals. He maintains that the cause of the former greater extension of the glaciers is to be sought in the fact, of which there are other independent proofs, that the land then stood at a far higher level than it does at present, an additional 3000 to 4000 feet being estimated to suffice for restoring the glaciers to their former maximum size. He likewise adduces grounds for believing that the glacier epoch (which he declines to regard as a *glacial* epoch) in New Zealand dates back to a much earlier time than the Ice Age of the northern hemisphere, probably to the Pliocene period.

To the Upper Pliocene and Pleistocene periods are assigned the wide terraced gravel-banks and alluvial flats which occur in the main valleys of Australia, and the great alluvial plains which in some of the colonies form such marked features. These deposits vary up to 300 feet in depth, and are a great storehouse of alluvial gold. They may possibly indicate that a greater rainfall was concerned in their formation than now characterises the same regions. If the glaciers of New Zealand advanced into the sea, and the great Antarctic ice-sheet ever crept north towards the Australian shores, during some part of this cold period, the rainfall may have been so augmented that the rivers spread out far beyond the limits within which they are now confined. Evidence indeed has been adduced in favour of true glaciation in the Australian Alps. What are described as ice-worn surfaces have been observed on Mount Cobboras at elevations of between 4000 and 6000 feet, and on Mount Kosciusko in New South Wales. Erratic blocks and moraines are likewise cited.[4]

Section ii. Recent, Post-glacial or Human Period.

§ 1. General Characters.

The long succession of Pleistocene ages shaded without abrupt change of any kind into what is termed the Human or Recent Period.[5] The Ice

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[1] Medlicott and Blanford, 'Geology of India,' p. 586.

[2] 'Geology of Canterbury and Westland,' p. 371. This however, as above stated, is not admitted by Captain Hutton (*N. Zealand Journ. Sci.* 1884).

[3] 'Geology of Otago,' p. 83. See for a fuller statement of his views on this subject his address on the Origin of the Fauna and Flora of New Zealand, *N. Zealand Journ. Sci.* (1884); also *Proc. Linn. Soc. N.S. Wales*, x. part 3.

[4] J. Stirling, *Trans. Roy. Soc. Vict.* 1884, p. 23 ; *Nature*, xxxv. (1886) p. 182 ; Dr. von Lendenfeld, *Proc. Linn. Soc. N.S. Wales*, 1885, p. 45.

[5] See for general information Lyell's 'Antiquity of Man,' Lubbock's 'Prehistoric Times,' Evans's 'Ancient Stone Implements,' Boyd Dawkins's 'Cave Hunting' and 'Early Man in Britain,' J. Geikie's 'Prehistoric Europe.'

Age, or Glacial Period, may indeed be said still to exist in Europe. The snow-fields and glaciers have disappeared from Britain, France, the Vosges, and the Harz, but they still linger among the Pyrenees, remain in larger mass among the Alps, and spread over wide areas in northern Scandinavia. This dovetailing or overlapping of geological periods has been the rule from the beginning of time, the apparently abrupt transitions in the geological record being due to imperfections in the chronicle.

The last of the long series of geological periods may be subdivided into subordinate sections as follows:—

Historic, up to the present time.
Prehistoric { Iron, Bronze, and later Stone.
Prehistoric { Neolithic.
Prehistoric { Palæolithic.

The Human Period is above all distinguished by the presence and influence of man. It is difficult to determine how far back the limit of the period should be placed. The question has often been asked whether man was coeval with the Ice Age. To give an answer, we must know within what limits the term Ice Age is used, and to what particular country or district the question refers. For it is evident that even to-day man is contemporary with the Ice Age in the Alpine valleys and in Finmark. There can be no doubt that he inhabited Europe after the greatest extension of the ice. He not improbably migrated with the animals that came from warmer climates into this continent during inter-glacial conditions. But that he remained when the climate again became cold enough to freeze the rivers and permit an Arctic fauna to roam far south into Europe is proved by the abundance of his flint implements in the thick river-gravels, into which they no doubt often fell through holes in the ice as he was fishing.

The proofs of the existence of man in former geological periods are not to be expected in the occurrence of his own bodily remains, as in the case of other animals. His bones are indeed now and then to be found, but in the vast majority of cases his former presence is revealed by the implements he has left behind him, formed of stone, metal, or bone. Many years ago the archæologists of Denmark, adopting the phraseology of the Latin poets, classified the early traces of man in three great divisions—the Stone Age, Bronze Age, and Iron Age. There can be no doubt that, on the whole, this has been the general order of succession in Europe, where men used stone and bone before they had discovered the use of metal, and learnt how to obtain bronze before they knew anything of the metallurgy of iron. Nevertheless, the use of stone long survived the introduction of bronze and iron. In fact, in European countries where metal has been known for many centuries, there are districts where stone implements are still employed, or where they were in use until quite recently. It is obvious also that, as there are still barbarous tribes unacquainted with the fabrication of metal, the Stone Age is not yet extinct in some parts of the world. In this instance, we again see how geological periods run into each other. The material or shape of the implement cannot therefore be always a very satisfactory proof of antiquity. We must judge of it by the circumstances under which it was found. From the fact that in north-western Europe the ruder kinds of stone weapons (Fig. 459) occur in what are certainly the older deposits, while others of more highly finished workmanship (Figs. 462, 463) are found in later accumulations, the Stone Age has been subdivided into an early or Palæolithic and a later or Neolithic epoch. There can be no doubt, however, that the latter was in great measure coeval with the age of bronze, and even, to some extent, with that of iron.[1]

The deposits which contain the history of the Human Period are river-alluvia, brick-earth, cavern-loam, calcareous tufa, loess, lake-bottoms, peat-mosses, sand-dunes, and other superficial accumulations.

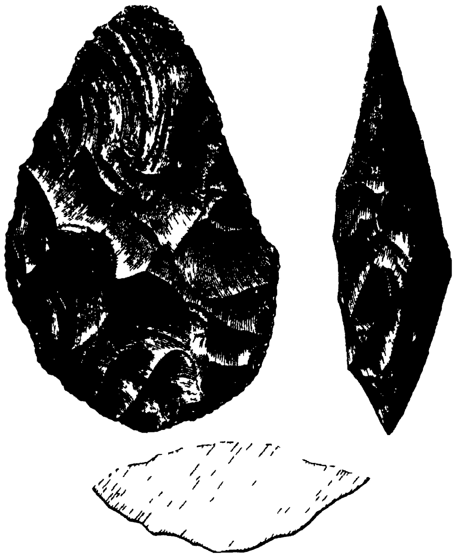

Fig. 459.—Palæolithic Flint Implement.

PALÆOLITHIC.[2]—Under this term are included those deposits which have yielded rudely-worked flints of human workmanship associated with the remains of mammalia, some of which are extinct, while others no longer live where their remains have been obtained. An association of the same mammalian remains under similar conditions, but without traces of man, may be assigned to the same geological period, and be included in the Palæolithic series. A satisfactory chronological classification of the deposits containing the first relics of man is perhaps unattainable, for these deposits occur in detached areas and offer no means of determining their physical sequence. To assert that a brick-earth is older than a cavern-breccia, because it contains some bones which the latter does not, or fails to show some which the latter does yield, is too often a conclusion drawn because it agrees with preconceptions.

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[1] The student may profitably consult Sir Arthur Mitchell's 'Past in the Present,' 1880, for the warnings it contains as to the danger of deciding upon the antiquity of an implement merely from its rudeness.

[2] This term has been further subdivided into minor sections according to the degree of "finish" in the instruments and their presumed chronological order. Thus, deposits containing the very rude type of worked flints found at Chelles near Paris and at St. Acheul have been called *Chellean* or *Acheulian*. Those with implements like the scrapers of Moustier (Dordogne) have been named *Mousterian*. Those where the flints have been more deftly worked, like the implements found at Solutré in Burgundy, have been called *Solutrian*; while those which contain well-finished implements associated with carved bone and ivory, as at the caves of La Madelaine (Périgord), have been called *Magdalenian*. But this classification does not rest on the evidence of superposition, and is probably of little chrono-

River-Alluvia.—Above the present levels of the rivers, there lie platforms or terraces of alluvium, sometimes up to a height of 80 or 100 feet. These deposits are fragments of the river-gravels and loams laid down when the streams flowed at these elevations, and therefore after the excavation of the valleys. The subsequent action of the running water has been to clear out much of the old alluvial material then accumulated, so as to leave the valleys widened and deepened to their present form. River-action is at the best but slow. To erode the valleys to so great a depth beneath the level of the upper alluvia, must have demanded a period of many centuries. There can therefore be no doubt of the high antiquity of these deposits. They have yielded the remains of many mammals, some of them extinct (*Elephas antiquus, Hippopotamus amphibius, Rhinoceros megarhinus* (*Merckii*), together with flint-flakes made by man. From the nature and structure of some of the high-level gravels there can be little doubt that they were formed at a time when the rivers, then possibly larger than now, were liable to be frozen and to be obstructed by accumulations of ice. We are thus able to connect the deposits of the Human Period with some of the later phases of the Ice Age in the west of Europe.

Brick-Earths.—In some regions that have not been below the sea for a long period, a variable accumulation of loam has been formed on the surface from the decomposition of the rocks *in situ*, aided by the drifting of fine particles by wind and the gentle washing action of rain and occasionally of streams. Some of these brick-earths or loams are of high antiquity, for they have been buried under fluviatile deposits which must have been laid down when the rivers flowed far above their present levels. They have yielded traces of man associated with bones of extinct mammals.

Cavern Deposits.—Most calcareous districts abound in underground tunnels and caverns which have been dissolved by the passage of water from the surface (p. 367). Where these cavities have communicated with the outer surface, terrestrial animals, including man himself, have made use of them as places of retreat, or have fallen or been washed into them. The floors of some of them are covered with a

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logical value, though some weight may be attached to the presence of different mammals with the different types of instrument.

reddish or brownish loam or cave-earth, resulting either from the insoluble residue of the rock left behind by the water that dissolved out the caverns, or from the deposit of silt carried by the water which in some cases has certainly flowed through them. Very commonly a deposit of stalagmite has formed from the drip of the roof above the cave-earth. Hence any organic remains which may have found their way to these floors have been sealed up and admirably preserved.

Calcareous Tufas.—The deposits of calcareous springs have in various parts of Europe preserved remains of the flora and fauna contemporaneous with the early human inhabitants of the Continent. Among the more celebrated of these deposits are those of Cannstadt in Würtemburg, which have yielded specimens of twenty-nine species of plants, consisting of oaks, poplars, maples, walnuts and other trees still living in the surrounding country, but with the remains of the extinct mammoth; and of La Celle, near Moret, in the valley of the Seine.

Loess.—The physical characters and probable æolian origin of this remarkable deposit having been already mentioned (p. 332), we may now consider it in reference to its place in geological history. In central Europe it covers a wide area. Beginning on the French coast at Sangatte, it sweeps eastward across the north of France and Belgium (Hesbayan loam), filling up the lower depressions of the Ardennes, passing far up the valleys of the Rhine and its tributaries, the Neckar, Main and Lahr; likewise those of the Elbe above Meissen, the Weser, Mulde, and Saale, the Upper Oder and the Vistula. Spreading across Upper Silesia, it sweeps eastward over the plains of Poland and southern Russia, where it forms the substratum of the Tschernosem or black-earth. It extends into Bohemia, Moravia, Hungary, Gallicia, Transylvania and Roumania, sweeping far up into the Carpathians, where it reaches heights of 2000 and, it is said, even 4000 or 5000 feet above the sea. It has not been observed on the low Germanic plains south of the Baltic, nor south of central France and the Alpine chain. Though thickest in the valleys (100 feet or more), it is not confined to them, but spreads over the plateaux and rises far up the flanks of the uplands. Near its edge, where it abuts against higher ground, it contains layers or patches of angular débris, but elsewhere it preserves a remarkable uniformity of texture.

The loess is sometimes found resting on gravels containing remains of the mammoth. It may be observed to shade off into more recent alluvial accumulations. It is probably not all of one age, having been deposited during a prolonged period and at many different altitudes. The older portions may not impossibly belong to the later part of the Glacial Period. Though on the whole not rich in fossils, the loess has yielded a peculiar fauna, which singularly confirms Richthofen's view that the deposit was a subaerial one. In the first place, the shells found in it are almost without exception of terrestrial species. Out of 211,968 specimens from the loess of the Rhine, Braun found only one brackish and three fresh-water forms, *Limnæa* and *Planorbis*, of which there were only 32 specimens in all. Of the rest, there were 98,502 examples of two species of *Succinea*, an amphibious genus, and 113,434 specimens belonging to 25 species of *Helix*, *Pupa*, *Clausilia*, *Bulimus*, *Limax*, and *Vitrina*—unquestionable terrestrial forms.[1] It is worthy of note that *Helices* and *Succineas* abound at present in the steppe-regions of central Asia, and that many of the species of loess mollusks are now living in east Russia, south-west Siberia, and on the prairies of the Little Missouri in North America.[2]

From various parts of the European loess, Dr. Nehring has described a remarkable assemblage of animals, which included a jerboa (*Alactaga jaculus*), marmots (*Spermophilus*, several species), *Arctomys bobac*, tailless hare (*Lagomys pusillus*), numerous species of *Arvicola*, *Cricetus frumentarius*, *C. phæus*, porcupine (*Hystrix hirsutirostris*), wild horses, and antelopes (*Antilope saiga*). This fauna, excepting some extinct or extirpated species, is identical with that which now lives in the south-east European and south-west Siberian steppes.[3] Besides these distinctively steppe animals the loess contains numerous remains of the mammoth and woolly rhinoceros, likewise bones of the musk-sheep, hare, wolf, stoat, &c. It has also yielded flint implements of Palæolithic types. The bones of man himself were claimed many years ago by Ami Boué to have been found in the loess, and his opinion has been in some measure strengthened by more recent observations.

The origin of the loess is a problem which has given rise to much discussion. It has been regarded by some writers as the deposit of a vast series of lakes; by others as the mud left by swollen rivers discharged from melting ice-fields; by others as a sediment washed over the surface of the land by an abundant rainfall. The remarkably unstratified character of the loess as a whole, its uniformity in fineness of grain, the general absence of coarse fragments, except along its margin, where they might be expected, its singular independence of the underlying contour of the ground, and the almost total absence in it of fluviatile or lacustrine shells, seem to prove conclusively that it cannot have been laid down by rivers or lakes. On the other hand, its internal composition, the thoroughly oxidised condition of its ferruginous constituent, its distribution, and the striking character of its enclosed organic remains, point to its having been accumulated in the open air, probably in circumstances similar to those which now prevail in the dry steppe regions of the globe. It appears to mark some arid interval after the height of the Glacial Period had passed away, when, whilst the climate still remained cold and the Arctic fauna had not entirely retreated to the north, a series of grassy and dusty steppes swept across the heart of Europe and Asia.[4]

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[1] *Zeitsch. fur die gesammt. Naturwiss.* xl. p. 45, as quoted by H. H. Howorth, *Geol. Mag.* 1882, p. 14.

[2] A. Nehring, *Geol. Mag.* 1883, p. 57; *Neues Jahrb.* 1889, p. 66.

[3] Nehring, *op. cit.* p. 51, where a reference to this author's numerous memoirs on the subject will be found.

[4] The views propounded by Richthofen for the loess of China and applied by Nehring to that of Europe have been widely adopted by geologists (see, for example, T. F. Jamieson,

Palæolithic Fauna.—The mammalian remains found in Palæolithic deposits are remarkable for a mixture of forms from warmer and colder latitudes similar to that already noted among the interglacial beds. It has been inferred, indeed, that the Palæolithic gravels are themselves referable to interglacial conditions. On the one hand, we meet with a number of species of warmer habitat, as the lion, hyæna, hippopotamus, lynx, leopard, and caffer cat; and, in the loess, the assemblage of forms above referred to as that which still characterises the warm dry steppes of south-eastern Europe and southern Siberia. But, on the other hand, a large number of the forms are northern, such as the glutton (*Gulo luscus*), Arctic fox (*Canis lagopus*), reindeer (*Cervus tarandus*), Alpine hare (*Lepus variabilis*), Norwegian lemming (*Myodes torquatus*), Arctic lemming (*M. lemmus*, *M. obensis*), marmot (*Arctomys marmotta*), Russian vole (*Arvicola ratticeps*), musk-sheep (*Ovibos moschatus*), snowy-owl (*Strix nyctea*). There is likewise a proportion of now wholly extinct animals, which include the Irish elk (*Cervus giganteus* or *Megaceros hibernicus*), *Elephas primigenius* (mammoth), *E. antiquus*, *Rhinoceros megarhinus*, *R. antiquitatis* (*tichorhinus*) (woolly rhinoceros), *R. leptorhinus*, and cave-bear (*Ursus spelæus*). The Palæolithic fauna has been divided into three sections, each supposed to correspond with a distinct period of time: 1st, the Age of *Elephas antiquus*, with which species are associated *Rhinoceros megarhinus* (*Merckii*) and *Hippopotamus amphibius* (*major*). 2nd, The Age of the mammoth, with the woolly rhinoceros, cave-bear and cave-hyæna. 3rd, The Age of the reindeer, when that animal passed in great numbers across central Europe. But, as already stated, such subdivisions are admittedly artificial, and should only be used as provisional aids in the comparison of deposits which cannot be tested by the law of superposition.

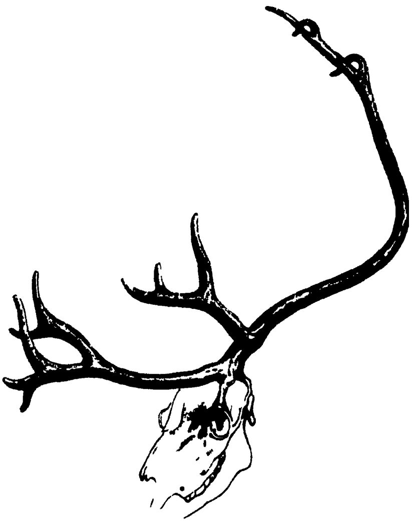

Fig. 460.—Antler of Reindeer (¼) found at Bilney Moor, East Dereham, Norfolk.

That man was contemporary with these various extinct animals is proved by the frequent occurrence of undoubtedly human implements, formed of roughly chipped flints, &c., associated with their bones.

Geol. Mag. 1890, p. 70). But they have not been universally received, some geologists contending that water in different ways has been concerned in the formation of the loess. See J. Geikie, 'Prehistoric Europe,' p. 244; *Rep. Brit. Assoc.* 1889; Address to Geol. Sect.; Wahnschaffe, *Zeitsch. Deutsch. Geol. Ges.* xxxviii. (1886) p. 583; F. Sacco, *Bull. Soc. Géol. France*, xvi. (1887) p. 229.

Much more rarely, portions of human skeletons have been recovered from the same deposits. The men of the time appear to have camped in rock-shelters and caves, and to have lived by fishing and by hunting the reindeer, bison, horse, mammoth, rhinoceros, cave-bear, and other animals. That they were not without some kind of culture is shown

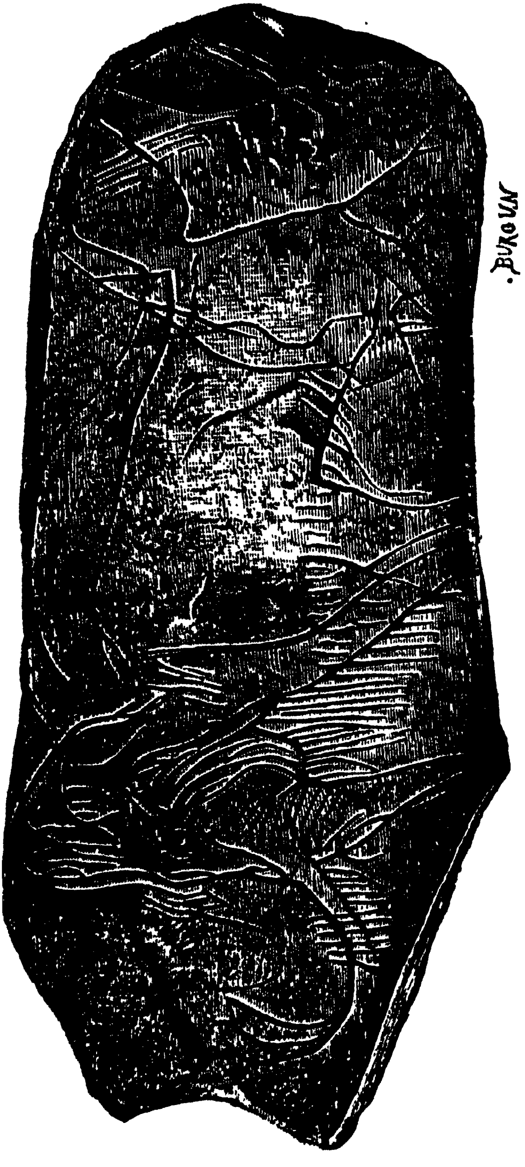

Fig. 461.—Figure of the Mammoth.

Engraved on Ivory by Cave-men La Madelaine, France (Lartet, 'Reliquiæ Aquitan').

by the vigorous incised sketches and carvings which they have left behind on reindeer antlers, mammoth tusks (Fig. 461), and other bones, depicting the animals with which they were daily familiar. Some of these drawings are especially valuable, as they represent forms of life long ago extinct, such as the mammoth and cave-bear. The men who in Palæolithic time inhabited the caves of Europe must have had much similarity, if not actual kinship, to the modern Eskimos.

NEOLITHIC.—The deposits whence the history of Neolithic man is compiled must vary widely in age. Some of them were no doubt contemporaneous with parts of the Palæolithic series, others with the Bronze and Iron series. They consist of cavern deposits, alluvial accumulations, peat-mosses, lake-bottoms, pile-dwellings, and shell-mounds.

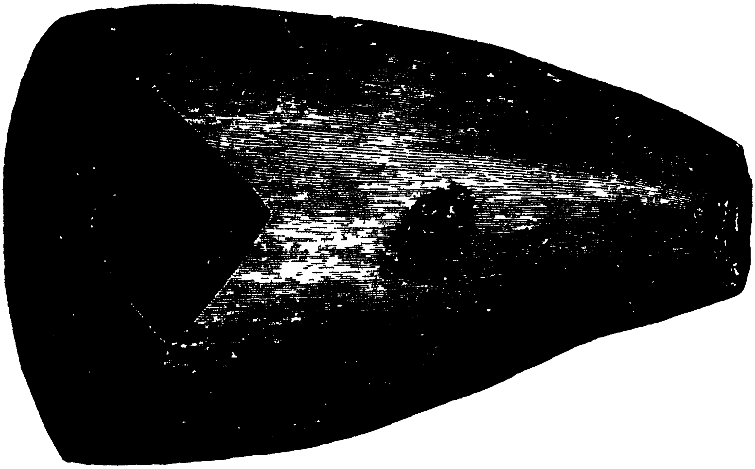

Fig. 462.—Neolithic Stone Implement.

The list of mammals, &c., inhabiting Europe during Neolithic is distinguished from that of Palæolithic time by the absence of the mammoth, woolly rhinoceros, and other extinct types, which appear to have meanwhile died out in Europe. The only form now extinct which appears to have survived into Neolithic time was the Irish elk, which may have continued to live until a comparatively late date.[1] The general assemblage of animals was probably much what it has been during the period of history, but with a few forms which have disappeared from most of Europe either within or shortly before the historic period, such as the reindeer, elk, urus, grizzly bear, brown bear, wolf, wild boar, and beaver. But besides these wild animals there are remains of domesticated forms introduced by the race which supplanted the Palæolithic tribes. These are the dog, horse, sheep, goat, shorthorn, and hog. It is noteworthy that these domestic forms were not parts of the indigenous fauna of Europe. They appear at once in the Neolithic deposits, leading to the inference that they were introduced by the human tribes which now migrated, probably from Central Asia, into the European continent. These tribes were likewise acquainted with agriculture, for several kinds of grain, as well as seeds of fruits, have been found in their lake-dwellings; and the deduction has been drawn from these remains that the plants must have been brought from southern Europe or Asia. The arts of spinning, weaving, and pottery-making were also known to these people. Human skeletons and bones belonging to this age have been met with abundantly in barrows and peat-mosses, and indicate that Neolithic man was of small stature, with a long or oval skull.

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[1] *Geol. Mag.* 1881, p. 354; *Nature*, xxvi. p. 246.

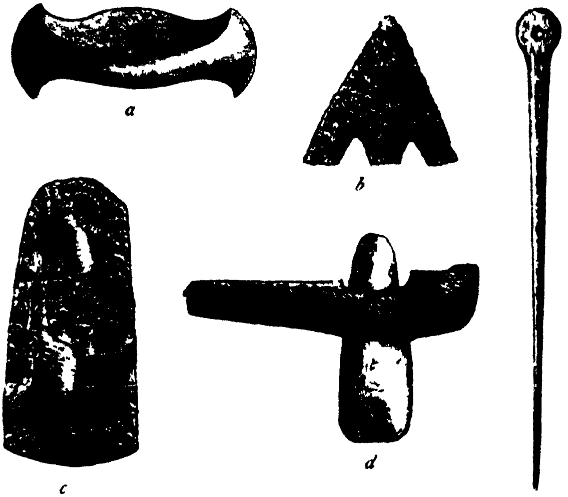

Fig. 463.- Neolothic Implements.

a, Stone axe-head (¼); *b*, Barbed flint arrow-head (natural size); *c*, Roughly-chipped flint celt (¼); *d*, Polished celt (¼), with part of its original wooden hand still attached, found in a peat-bog, Cumberland; *e*, Bone-needle (natural size), Swiss Lake Dwellings; *a*, *b*, *c*, *d*, reduced from Sir J. Evans's "Ancient Stone Implements."

The history of the Bronze and Iron Ages in Europe is told in great fulness, but belongs more fittingly to the domain of the archæologist, who claims as his proper field of research the history of man upon the globe. The remains from which the record of these ages is compiled are objects of human manufacture, graves, cairns, sculptured stones, &c., and their relative dates have in most cases to be decided, not upon geological, but upon archæological grounds. When the sequence of human relics can be shown by the order in which they have been successively entombed, the inquiry is strictly geological, and the reasoning is as logical and trustworthy as in the case of any other kind of fossils. Where, on the other hand, as so often happens, the question of antiquity has to be decided solely by relative finish and artistic character of workmanship, it must be left to the experienced antiquary.

§ 2. Local Development.

A few examples of the nature of the deposits of the Palæolithic and Neolithic series will suffice to show the general character of the evidence which they supply.

Britain.—Palæolithic deposits are absent from the north of England and from Scotland. They occur in the south of England, and notably in the valley of the Thames. In that district, a series of brick-earths with intercalated bands of river-gravel, having a united thickness of more than 25 feet, is overlain with a remarkable bed of clay, loam, and gravel ("trail"), three feet or more in thickness, which in its contorted bedding and large angular blocks probably bears witness to its having been accumulated during a time of floating ice. The strata below this presumably glacial deposit have yielded a remarkable number of mammalian bones, among which have been found undoubted human implements of chipped flint. The species include *Rhinoceros leptorhinus*, *R. antiquitatis* (*tichorhinus*), *R. megarhinus*, *Elephas antiquus*, *E. primigenius*, *Cervus giganteus* (*Megaceros hibernicus*), *Felis leo*, *Hyæna crocuta*, *Ursus ferox*, *U. arctos*, *Ovibos moschatus*, *Hippopotamus amphibius* (*major*), and present another example of the mingling of northern with southern, and of extinct with still living forms, as well as of species which have long disappeared from Britain with others still indigenous. Other ancient alluvia, far above the present levels of the rivers, have likewise furnished similar evidence that man continued to be the contemporary in England of the northern rhinoceros and mammoth, the reindeer, grizzly bear, brown bear, Irish elk, hippopotamus, lion, and hyæna.

The caverns in the Devonian, Carboniferous, and Magnesian limestones of England have yielded abundant relics of the same prehistoric fauna, with associated traces of Palæolithic man. In some of these places, the lowest deposit on the floor contains rude flint implements of the same type as those found in the oldest river-gravels, while others of a more finished kind occur in overlying deposits, whence the inference has been drawn that the caverns were first tenanted by a savage race of extreme rudeness, and afterwards by men who had made some advance in the arts of life. The association of bones shows that when man had for a time retired, some of these caves became hyæna dens. Hyæna bones in great numbers have been found in them (remains of no fewer than 300 individuals were taken out of the Kirkdale cave), with abundant gnawed bones of other animals on which the hyænas preyed, and quantities of their excrement. Holes in the limestone opening to the surface (sinks, swallow-holes) have likewise become receptacles for the remains of many generations of animals which fell into them by accident, or crawled into them to die. In a fissure of the limestone near Castleton, Derbyshire, from a space measuring only 25 by 18 feet, no fewer than 6800 bones, teeth, or fragments of bone were obtained, chiefly bison and reindeer, with bears, wolves, foxes, and hares.[1]

France.—It was in the valley of the Somme, near Abbeville, that the first observations were made which led the way to the recognition of the high antiquity of man upon the earth. That valley has been eroded out of the Chalk, which rises to a height of from 200 to 300 feet above the modern river. Along its sides, far above the present alluvial plain, are ancient terraces of gravel and loam, formed at a time when the river flowed at higher levels. The lower terrace of gravel, with a covering of flood-loam, ranges from 20 to 40 feet in thickness, while the higher bed is about 30 feet. Since their formation, the Somme has eroded its channel down to its present bottom, and may have also diminished in volume, while the terraces have, during the interval, here and there suffered from denudation. Flint implements have been obtained from both terraces, and in great numbers, associated with bones of mammoth, rhinoceros and other extinct mammals (p. 1047).

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[1] Boyd Dawkins, 'Early Man in Britain,' p. 188. The reindeer has yet not been found in such abundance in the English caverns as in those of Southern France.

The caverns of the Dordogne and other regions of the south of France have yielded abundant and varied evidence of the coexistence of man with the reindeer and other animals either wholly extinct or no longer indigenous. So numerous in particular are the reindeer remains, and so intimate the association of traces of man with them, that the term "Reindeer period" has been proposed for the section of prehistoric time to which these interesting relics belong. The art displayed in the implements found in the caverns appears to indicate a considerable advance on that of the chipped flints of the Somme. Some of the pictures of reindeer and mammoths, incised on bones of these animals, are singularly spirited (Fig. 461).

Germany.—From various caverns, particularly in the dolomite of Franconia (Muggendorf, Gailenreuth) and in the Devonian limestone of Westphalia and Rhineland, remains of extinct mammals have been obtained, sometimes in great numbers, including cave-bear (of which the remains of 800 individuals have been taken out of the Gailenreuth cave), hyæna, lion, rhinoceros, and others. From the cavern of Hohlefels in Swabia remains of elephants, rhinoceroses, reindeer, antelopes, horses, cave-bears and other animals have been found, together with interesting proofs of the contemporaneity of man, in the form of rude flint implements, axes of bone, or teeth and bones which he had bored through, or split open for their marrow. At Schussenried in the Swabian Saulgau, not far from the Lake of Constance, beneath a deposit of calcareous tufa enclosing land-shells, there is a peaty bed containing Arctic and Alpine mosses, together with abundant remains of reindeer, also bones of the glutton, Arctic fox, brown fox, polar bear, horse, &c. While this truly Arctic assemblage of animals lived near the foot of the Alps, man also was their contemporary, as is shown by the presence, in the same deposit, of his flint implements, stones that have been blackened by fire, bones of the reindeer and horse that have been broken open for their marrow, needles of wood and bone, and balls of red pigment probably used for painting his body.[1]

Switzerland.—The lakes of Switzerland, as well as those of most other countries in Europe, have yielded in considerable numbers the relics of Neolithic man. Dwellings constructed of piles were built in the water out of arrow-shot from the shore. Partly from destruction by fire, partly from successive reconstructions, the bottom of the water at these places is strewn with a thick accumulation of débris, from which vast numbers of relics of the old population have been recovered, revealing much of their mode of life.[2] Some of these settlements probably date far back beyond the beginning of the historic period. Others belong to the Bronze, and to the Iron Age. But the same site would no doubt be used for many generations, so that successive layers of relics of progressively later age would be deposited on the lake-bottom. It is believed that in some cases the lacustrine dwellings were still used in the first century of our era.

Denmark.—The shell-mounds (*Kjokken-modding*), from 3 to 10 feet high, and sometimes 1000 feet long, heaped up on various parts of the Danish coast-line, mark settlements of the Neolithic age. They are made up of refuse, chiefly shells of mussels, cockles, oysters, and periwinkles, mingled with bones of the herring, cod, eel, flounder, great auk, wild duck, goose, wild swan, capercailzie, stag, roe, wild boar, urus, lynx, wolf, wild cat, bear, seal, porpoise, dog, &c., with human tools of stone, bone, horn, or wood, fragments of rude pottery, charcoal, and cinders.

The Danish peat-mosses have likewise furnished relics of the early human races in that region. They are from 20 to 30 feet thick, the lower portion containing remains of Scotch fir (*Pinus sylvestris*) and Neolithic implements. This tree has never been indigenous in the country within the historic period. A higher layer of the peat contains remains of the common oak with bronze implements, while at the top come the beech-tree and weapons of iron.[1]

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[1] O. Fraas, *Archiv für Anthropologie*, Brunswick, 1867.

[2] Keller's 'Lake Dwellings of Switzerland.'

North America.—Prehistoric deposits are essentially the same on both sides of the Atlantic. In North America, as in Europe, no very definite lines can be drawn within which they should be confined. They cannot be sharply separated from the Champlain series on the one hand, nor from modern accumulations on the other. Besides the marshes, peat-bogs, and other organic deposits which belong to an early period in the human occupation of America, some of the younger alluvia of the river-valleys and lakes can no doubt claim a high antiquity, though they have not supplied the same copious evidence of early man which gives so much interest to the corresponding European formations. From the peat-bogs of the eastern States, and from the older alluvium of the Missouri River, the remains of the gigantic mastodon have been obtained. There have likewise been found bones of reindeer, elk, bison, beaver, horse (six species), lion and bear; while southwards those of extinct sloths (*Mylodon*, *Megatherium*) make their appearance. In California, from the deep auriferous gravels remains of mastodon and other extinct animals have been met with, also human bones, stone spear-heads, mortars and other implements. Prof. Whitney has described the famous Calaveras skull as occurring at a depth of 120 feet in undisturbed gravel which is covered with a sheet of basalt.[2] Heaps of shells of edible species, like those of Denmark, occur on the coasts of Nova Scotia, Maine, &c. The large mounds of artificial origin in the Mississippi valley have excited much attention. The early archæology of these regions is full of interest.

In South America, the loams of the Pampas have furnished abundant remains of horses, tapirs, lamas, mastodons, wolves, panthers, with gigantic extinct sloths and armadillos (*Megatherium*, *Glyptodon*).[3]

Australasia.—No line can be drawn in this region between accumulations of the present time and those which have been called Pleistocene. The modern alluvia have been formed under similar conditions to those under which the older alluvia were laid down, though possibly with some differences of climate. In New South Wales, ossiferous caverns contain bones of the extinct marsupial animals mentioned on p. 1022, mingled with those of some of the species which are still living in the same places. In one locality in the same colony, in sinking a well, teeth of crocodiles were found with bones of *Diprotodon*, &c. No human remains have yet been found associated with those of the extinct animals; but a stone hatchet was taken out of alluvium at a depth of 14 feet.[4]

In New Zealand, the most interesting feature in the younger geological accumulations is the presence of the bones of the large bird *Dinornis*, which has become extinct since the Maoris peopled the islands. The evidences of the human occupation of the country are confined to the surface-soil, shelter-caves, and sand-dunes.[5]

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[1] See Steenstrup on "Kjokken Moddinger"; Nathorst, *Nature*, 1889, p. 453.

[2] *Mem. Mus. Compar. Zool. Harvard*, vi. (1880). But the age of this relic is the subject of dispute. The evidence adduced in support of the great antiquity of man in America, and his contemporaneity with the Mastodon and other extinct animals, is summarised by the Marquis de Nadaillac in his 'L'Amérique Préhistorique' (translated by N. d'Anvers, 1885).

[3] See Florentino Ameghino, 'La Antiquedad del Hombre en el Plata,' where a good account of the Pampas country will be found.

[4] C. S. Wilkinson, 'Notes on Geology of New South Wales, 1882,' p. 59.

[5] Hector, 'Handbook of New Zealand,' p. 25.

BOOK VII.

PHYSIOGRAPHICAL GEOLOGY.

AN investigation of the geological history of a country involves two distinct lines of inquiry. We may first consider the nature and arrangement of the rocks that underlie the surface, with a view to ascertain from them the successive changes in physical geography and in plant and animal life which they chronicle. But besides the story of the rocks, we may try to trace that of the surface itself—the origin and vicissitudes of the mountains and plains, valleys and ravines, peaks, passes, and lake-basins which have been formed out of the rocks. The two inquiries traced backward merge into each other; but they become more and more distinct as they are pursued towards later times. It is obvious, for instance, that a mass of marine limestone which rises into groups of hills, trenched by river-gorges and traversed by valleys, presents two sharply contrasted pictures to the mind. Looked at from the side of its origin, the rock brings before us a sea-bottom over which the relics of generations of a luxuriant marine calcareous fauna accumulated. We may be able to trace every bed, to mark with precision its organic contents, and to establish the zoological succession of which these superimposed sea-bottoms are the records. But we may be quite unable to explain how such sea-formed limestone came to stand as it now does, here towering into hills and there sinking into valleys. The rocks and their contents form one subject of study; the history of their present scenery forms another.

The branch of geological inquiry which deals with the evolution of the existing contours of the dry land is termed Physiographical Geology. To be able to pursue it profitably, some acquaintance with all the other branches of the science is requisite. Hence its consideration has been reserved for this final division of the present work; but only a rapid summary can be attempted here.

At the outset one or two fundamental facts may be stated. It is evident that the materials of the greater part of the dry land have been laid down upon the floor of the sea. That they now not only rise above the sea-level, but sweep upwards into the crests of lofty mountains, can only be explained by displacement. Thus the land owes its existence mainly to upheaval of the terrestrial crust, though it may have been to some extent increased and diminished by other causes (*ante*, pp. 282, 292). The same sedimentary materials which demonstrate the fact of displacement, afford an indication of its nature and amount. Having been laid down in wide sheets on the sea-bottom, they must have been originally, on the whole, level or at least only gently inclined. Any serious departure from this original position must therefore be the effect of displacement, so that stratification forms a kind of datum-line from which such effects may be measured.

Further, it is not less apparent that sedimentary rocks, besides having suffered from disturbance of the crust, have undergone extensive denudation. Even in tracts where they remain horizontal, they have been carved into wide valleys. Their detached outliers stand out upon the plains as memorials of what has been removed. Where, on the other hand, they have been thrown into inclined positions, the truncation of their strata at the surface points to the same universal degradation. Here, again, the lines of stratification may be used as datum-lines to measure approximately the amount of rock which has been worn away.

While, therefore, it is true that, taken as a whole, the dry land of the globe owes its existence to upheaval, it is not less true that its present contours are due largely to erosion. These two antagonistic forms of geological energy have been at work from the earliest times, and the existing land with all its varied scenery is the result of their combined operation. Each has had its own characteristic task. Upheaval has, as it were, raised the rough block of marble, but erosion has carved that block into the graceful statue.

The very rocks of which the land is built up bear witness to this intimate co-operation of hypogene and epigene agency. The younger stratified formations have been to a large extent derived from the waste of the older, the same mineral ingredients being used over and over again. This could not have happened but for repeated uplifts, whereby the sedimentary accumulations of the sea-floor were brought within reach of the denuding agents. Moreover, the internal characters of these formations point unmistakably to deposition in comparatively shallow water. Their abundant intercalations of fine and coarse materials, their constant variety of mineral composition, their sun-cracks, ripple-marks, rain-pittings, and worm-tracks, their numerous unconformabilities and traces of terrestrial surfaces, together with the prevalent facies of their organic contents, combine to demonstrate that the main mass of the sedimentary rocks of the earth's crust was accumulated close to land, and that no trace of really abysmal deposits is to be found among them. From these considerations we are led up to the conclusion that the present continental areas must have been terrestrial regions of the earth's surface from a remote geological period. Subject to repeated oscillations, so that one tract after another has disappeared and reappeared from beneath the sea, the continents, though constantly varying in shape and size, have yet, I believe, maintained their individuality. We may infer, likewise, that the existing ocean-basins have probably always been the great depressions of the earth's surface.[1]

Geologists are now generally agreed that it is mainly to the effects of the secular contraction of our planet that the deformations and dislocations of the terrestrial crust are to be traced. The cool outer shell has sunk down upon the more rapidly contracting hot nucleus, and the enormous lateral compression thereby produced has thrown the crust into undulations, and even into the most complicated corrugations.[2] Hence, in the places where the crust has yielded to the pressure, it must have been thickened, being folded or pushed over itself, or being perhaps thrown into double bulges, one portion of which rises into the air, while the corresponding portion descends into the interior. Mr. Fisher believes that this downward bulging of the lighter materials of the crust into a heavier substratum underneath the great mountain-uplifts of the surface is indicated by the observed diminution in the normal rate of augmentation of earth-temperature beneath mountains,[3] and by the lessened deflection of the plumb-line in the same regions.

The close connection between upheaval and denudation on the one hand and depression and deposition on the other has often been remarked, and striking examples of it have been gathered from all parts of the world. It is a familiar fact that along the central and highest parts of a mountain chain, the oldest strata have been laid bare after the removal of an enormous thickness of later deposits. The same region still remains high ground, even after prolonged denudation. Again, in areas where thick accumulations of sedimentary material have taken place, there has always been contemporaneous subsidence. So close and constant is this relationship, as to have suggested the belief that denudation by unloading the crust allows it to rise, while deposition by loading it causes it to sink (*ante*, p. 295).[4]

It is evident that in the results of terrestrial contraction on the surface of the whole planet, subsidence must always have been in excess of upheaval—that in fact upheaval has only occurred locally over areas where portions of the crust have been ridged up by the enormous tangential thrust of adjacent subsiding regions. The tracts which have thus been, as it were, squeezed out under the strain of contraction have been weaker parts of the crust, and have usually been made use of again and again during geological time. They form the terrestrial regions of the earth's surface. Thus, the continents as we now find them are the result of many successive uplifts, corresponding probably to concomitant depressions of the ocean bed. In the long process of contraction, the earth has not contracted uniformly and equably. There have been, no doubt, vast periods during which no appreciable or only excessively gradual movements took place; but there have probably also been intervals when the accumulated strain on the crust found relief in more or less rapid collapse.

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[1] See J. D. Dana, *Amer. Journ. Sci.* (2) ii. (1846) p. 352; "Geology" in 'Wilkes' Exploring Expedition,' 1849; *Amer. Journ. Sci.* (2) xxii. (1856); 'Manual of Geology,' 1863, 2nd edit. 1874, 3rd edit. 1880; Darwin, 'Origin of Species,' 1st edit. p. 343; L. Agassiz, *Bull. Mus. Comp. Zool.* 1869, vol. i. No. 13; J. D. Whitney, *Mem. Mus. Comp. Zool. Harvard*, vii. No. 2, p. 210. See also *Proc. Roy. Geograph. Soc.* new ser. i. (1879) p. 422. The contrary view that land and sea have continually changed places over the surface of the globe was held by Lyell, and is still maintained by some geologists. For a statement of geological evidence in favour of this interchange of terrestrial and marine areas the student may consult the memoirs of the late Professor Neumayr, cited on p. 895.

[2] The Rev. O. Fisher in his 'Physics of the Earth's Crust,' maintains that the secular contraction of a solid globe through mere cooling will not account for the observed phenomena. See *ante*, p. 56.

[3] The rate observed in the Mont Cenis and Mont St. Gothard tunnels was about 1° Fahr. for every 100 feet, or only about half the usual rate.

[4] This belief has been forcibly urged by American geologists who have studied the structure of the Western Territories. See especially the geological Reports of Mr. Clarence King, Major Powell, and Captain Dutton; also Mr. T. Mellard Reade's 'Origin of Mountain-Ranges,' and *Phil. Mag.* June 1891.

The general result of such terrestrial disturbances has been to throw the crust of the earth into wave-like undulations. In some cases, a wide area has been upheaved as a broad low arch, with little disturbance of the original level stratification of its component rocks. More usually, the undulations have been impressed as more sensible deformations of the crust, varying in magnitude from the gentlest appreciable roll up to mountainous crests of complicated plication, inversion, and fracture. As a rule, the undulations have been linear, but their direction has varied from time to time, having been determined at right angles, or approximately so, to the trend of the lateral pressure that produced them. As the crust has thickened, and in consequence of the structure imparted to it by successive subsidences, certain tracts even of the land have acquired more or less immobility, and have served as buttresses against which surrounding areas have been pressed and dislocated by subsequent movements. Suess has pointed out various areas of the earth's surface, named by him "Horsts," which seem to have served this purpose in the general rupture and subsidence of the terrestrial crust.

Considered with reference to their mode of production, the leading contours of a land-surface may be grouped as follows: 1. Those which are due more or less directly to disturbance of the crust. 2. Those which have been formed by volcanic action. 3. Those which are the result of denudation.[1]

1. Terrestrial Features due more or less directly to Disturbance of the Crust.—In some regions, large areas of stratified rocks have been raised up with so little trace of curvature, that they seem to the eye to extend in horizontal sheets as wide plains or tablelands. If, however, these areas can be followed sufficiently far, the flat strata are eventually found to curve down slowly or rapidly, or to be truncated by dislocations. In an elevated region of this kind, the general level of the ground corresponds, on the whole, with the planes of stratification of the rocks. Vast regions of Western America, where

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[1] For a sketch of the physiography of the British Isles see *Nature*, xxix. (1884) pp. 325, 347, 396, 419, 442.

Cretaceous and later strata extend in nearly horizontal sheets for thousands of square miles at heights of 4000 feet or more above the sea, may be taken as illustrations of this structure.

As a rule, curvature is more or less distinctly traceable in every region of uplifted rocks. Various types of flexure may be noticed, of which the following are some of the more important:—

(*a*) *Monoclinal Flexures* (p. 538).—These occur most markedly in broad plateau-regions and on the flanks of large broad uplifts, as in the table-lands of Utah, Wyoming, &c. They are frequently replaced by faults, of which indeed they may be regarded as an incipient stage (p. 551).

(*b*) *Symmetrical Flexures*, where the strata are inclined on the two sides of the axis at the same or nearly the same angle, may be low gentle undulations, or may increase in steepness till they become short sharp curves. Admirable illustrations of different degrees of inclination may be seen in the ranges of the Jura[1] (Fig. 464) and the Appalachians (Fig. 246), where the influence of this structure of the rocks on external scenery may be instructively studied. In many instances, each anticline forms a long ridge, and each syncline runs as a corresponding and parallel valley. It will usually be observed, however, that the surface of the ground does not strictly conform, for more than a short distance, to the surface of any one bed; but that, on the contrary, it passes across the edges of successive beds, as in Fig. 464. This relation—so striking a proof of the extent to which the surface of the land has suffered from denudation—may be followed through successive phases until the original superficial contours are exactly reversed, the ridges running along the lines of syncline and the valleys along the lines of anticline (Figs. 244, 245). Among the older rocks of the earth's crust which have been exposed alike to curvature and prolonged denudation, this reversal may be considered to be the rule rather than the exception. The tension of curvature may occasionally have produced an actual rupture of the crest of an anticline along which the denuding agents would effectively work.

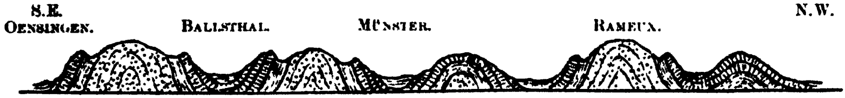

Fig. 464.—Symmetrical Flexures of Swiss Jura (the ridges coinciding with anticlines and the valleys with synclines).

The *Uinta type* is a variety of this structure seen to great perfection in the Uinta Mountains of Wyoming and Utah. It consists of a broad flattened flexure from which the strata descend steeply or vertically into the low grounds, where they quickly resume their horizontality. In the Uinta Mountains, the flat arch has a length of upwards of 150 and a breadth of about 50 miles, and exposes a vast deeply trenched plateau with an average height of 10,000 to 11,000 feet above the sea, and 5000 to 6000 feet above the plains on either side. This elevated region consists of nearly level ancient Palæozoic rocks, which plunge below the Secondary and Tertiary deposits that have been tilted by the uplift (Fig. 465). Powell believes that a depth of not less than three and a half miles of strata has been removed by denudation from the top of the arch.[1] In some places, the line of maximum flexure at the side of the uplift has given way, and the resulting fault has at one point a vertical displacement estimated by him at 20,000 feet.

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[1] On the geology of the Jura see C. Clerc, 'Le Jura,' Paris, 1888; G. Boyer, 'Remarques sur l'Orographie des Monts Jura,' Besançon, 1888; and the older work of Thurmann, 'Esquisses Orographiques de la Chaine du Jura,' 1852.

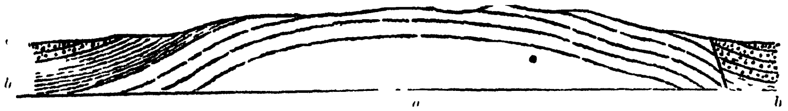

Fig. 465.—Uinta Type of Flexure.
a, Palæozoic rocks; b, Mesozoic; c, Tertiary; f, fault

Another variety of more complex structure may be termed the *Park type*, from its singularly clear development in the Park region of Colorado. In this type, an axis of ancient crystalline rocks—granites, gneisses, &c.—has been as it were pushed through the flexure, or the younger strata have been bent sharply over it, so that after vast denudation their truncated ends stand up vertically along the flanks of the uplifted nucleus of older rocks (Fig. 466).

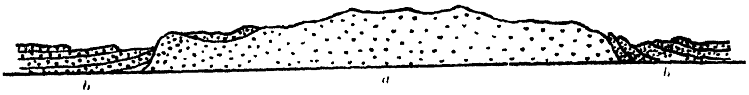

Fig. 466. Park Type of Flexure.
a, Crystalline rocks, b, Mesozoic rocks.

There may be only one dominant flexure, as in the case of the Uinta Mountains, the long axial line of which is truncated at the ends by lines of flexure nearly at right angles to it. More usually, numerous folds run approximately parallel to each other, as in the Jura and Appalachian chains. Not infrequently, some of them die out or coalesce. Their axes are seldom perfectly straight lines.

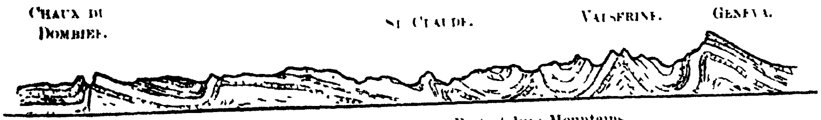

Fig. 467.—Section across Western Part of Jura Mountains.
(After P. Choffat, from A. Heim, 'Mechanism. Gebirgsb.' pl. xiii.)

(c) *Unsymmetrical Flexures*, where one side of the fold is much steeper than the other, but where they are still inclined in opposite directions, occur in tracts of considerable disturbance. The steep sides look away from the area of maximum movement, and are more sharply inclined as they approach it, until the flexures become inverted. Instructive examples of this structure are presented by the Jura Mountains and the Appalachian chain. In these tracts, it is observable that in proportion as the flexures increase in angle of inclination, they become narrower and closer together; while, on the other hand, as they diminish into symmetrical forms, they become broader, flatter, and wider apart, till they disappear (Figs. 246, 467).

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[1] 'Geology of Uinta Mountains,' p. 201. There is in this work a suggestive discussion on types of mountain structure. See also Clarence King's 'Report on Geology of 40th Parallel,' vol. i.

(*d*) *Reversed Flexures*, where the strata have been folded over in such a way that on both sides of the axis of curvature they dip in the same direction, occur chiefly in districts of the most intense plication, such as a great mountain chain like the Alps. The inclination, as before, is for the most part towards the region of maximum disturbance, and the flexures are often so rapid that after denudation of the tops of the arches the strata are isoclinal, or appear to be dipping all in the same direction (p. 540). A gradation can be traced through the three last-named kinds of flexure. The inverted or reversed type is found where the crumpling of the crust has been greatest. Away from the area of maximum disturbance, the folds pass into the unsymmetrical type, then with gradually lessening slopes into the symmetrical, finally widening out and flattening into the plains. If we bisect the flexures in a section of such a plicated region we find that the lines of bisection or "axis-planes" are vertical in the symmetrical folds, and gradually incline towards the more plicated ground at lessening angles.[1]

Fractures not infrequently occur along the axes of unsymmetrical and inverted flexures, the strata having snapped under the great tension, and one side (in the case of inverted flexures, usually the upper side), having been pushed over the other, sometimes with a vertical displacement of several thousand feet, or a horizontal thrust of several miles. It is along or parallel to the axes of plication, and therefore coincident with the general strike, that the great faults of a plicated region occur. As a rule, dislocations are more easily traced among low grounds than among the mountains. One of the most remarkable and important faults in Europe, for example, is that which bounds the southern edge of the Belgian coal-field (p. 835). It can be traced across Belgium, has been detected in the Boulonnais, and may not improbably run beneath the Secondary and Tertiary rocks of the south of England. The extraordinary thrust-planes of the north-west of Scotland (pp. 625, 706) are notable examples of gigantic horizontal displacement. It is a remarkable fact that faults which have a vertical throw of many thousands of feet may produce little or no effect upon the surface. The great Belgian fault is crossed by the valleys of the Meuse and other northerly flowing streams, yet so indistinctly is it marked in the Meuse valley that no one would suspect its existence from any peculiarity in the general form of the ground, and even an experienced geologist, until he had learned the structure of the district, would scarcely detect any fault at all. The Scottish thrust-planes are eroded like ordinary junction-planes between strata, and produce no more effect than these do on the topography (see Figs. 311, 334).

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[1] H. D. Rogers, *Trans. Roy. Soc. Edin.* xxi. p. 434.

In some regions of intense disturbance, such as the Alps, the rocks have been plicated rather than fractured. The folds have been so compressed that their opposite limbs often lie parallel to each other at a high inclination. In other regions, such as the north-west of Scotland, where the gigantic pressure has encountered the resistance of a "horst" or solid buttress of immovable material, the rocks have been ruptured by innumerable thrust-planes and faults, and have been driven over each other in a kind of imbricated structure (p. 624).

(*e*) *Alpine Type of Mountain-Structure*.[1]—It is along a great mountain chain like the Alps that the most colossal crumplings of the terrestrial crust are to be seen. In approaching such a chain, one or more minor ridges may be observed running on the whole parallel with it, as the heights of the Jura flank the north side of the Alps, and the sub-Himalayan hills follow the southern base of the Himalayas. On the outer side of these ridges, the strata may be flat or gently inclined. At first they undulate in broad gentle folds; but traced towards the mountains these folds become sharper and closer, their shorter sides fronting the plains, their longer slopes dipping in the opposite direction. This inward dip is often traceable along the flanks of the main chain of mountains, younger rocks seeming to underlie others of much older date. Along the north front of the Alps, for instance, the red molasse is overlain by Eocene and older formations. The inversions increase in magnitude till they reach such colossal dimensions as the double fold of the Glärnisch, where Triassic, Jurassic, and Cretaceous rocks have been thrown over above the Eocene flysch and nummulitic limestone (p. 539). In such vast crumplings it may happen that portions of older strata are caught in the folds of later formations, and some care may be required to discriminate the enclosure from the rocks of which it appears to form an integral and original part. Some of the recorded examples of fossils of an older zone occurring by themselves in a much younger group of plicated rocks may be thus accounted for.

The inward dip and consequent inversion traceable towards the centre of a mountain chain lead up to the fan-shaped structure (p. 541), where the oldest rocks of a series occupy the centre and overlie younger masses which plunge steeply under them. Classical examples of this structure occur in the Alps (Mont Blanc, Fig. 250, St. Gothard), where crystalline rocks such as granite, gneiss, and schist, the oldest masses of the chain, have been ridged up into the central and highest peaks. Along these tracts, denudation has been of course enormous, for the appearance of the granitic rocks at the surface has been brought about, not necessarily by actual extrusion into the air, but more probably by prolonged erosion, which in these higher regions, where many forms of sub-aerial waste reach their most vigorous phase, has removed the vast overarching cover of younger rocks under which the crystalline nucleus doubtless lay buried.

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[1] For recent information on the internal structure of the Alpine chain see especially the maps, sections, and explanatory memoirs by Renevier, Heim, A. Baltzer, E. Favre, K. J. Kaufmann, C. Moesch, H. Schardt, A. Gutzwiller, and others in the *Beiträge zur Geol. Karte der Schweiz*; also Fritz Frech, "Die Karnischen Alpen," *Abhand. Naturf. Ges. Halle*, xviii. (Heft i.) 1892; Zaccagna on the Graian Alps, *Boll. Com. Geol. Ital.* ser. iii. vol. iii. (1892) p. 175; consult also Heim's 'Mechanismus der Gebirgsbildung'; Suess, 'Antlitz der Erde' and 'Entstehung der Alpen'; A. Favre, 'Recherches Géol. dans les parties de la Savoie du Piémont et de la Suisse voisines du Mont Blanc,' 1867, and 'Description Géol. Canton Genève,' 1880.

With the crumpling and fracture of rocks in mountain-making, the hot springs must be connected, which so frequently arise along the flanks of a mountain chain. A further relation is to be traced between these movements and the opening of volcanic vents either along the chain or parallel to it, as in the Andes and other prominent ridges of the crust. Elevation, by diminishing the pressure on the parts beneath the upraised tracts, may permit them to assume a liquid condition and to rise within reach of the surface, when, driven upwards by the expansion of superheated vapours, they are ejected in the form of lava or ashes. Mr. Fisher supposes that the lower half of the double bulge of the crust in a mountain, by being depressed into a lower region, may be melted off, giving rise to siliceous lavas which may rise before the deeper basaltic magma begins to be erupted.

A mountain-chain may be the result of one movement, but probably in most cases is due to a long succession of such movements. Formed on a line of weakness in the crust, it has again and again given relief from the strain of compression by undergoing fresh crumpling and upheaval. The successive stages of uplift are usually not difficult to trace. The chief guide is supplied by unconformability (p. 641). Let us suppose, for example, that a mountain range (Fig. 468) consists of

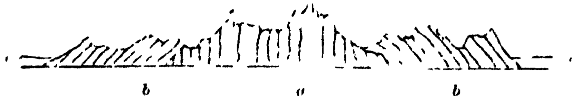

Fig. 468. Section showing two periods of Upheaval.

upraised Lower Silurian rocks (*a*), upon the upturned and denuded edges of which the Carboniferous Limestone (*b b*) lies transgressively. The original upheaval of that range must have taken place between the Lower Silurian and the Carboniferous Limestone periods. If, in following the range along its course, we found the Carboniferous Limestone also highly inclined and covered unconformably by the Upper Coal-measures (*c c*), we should know that a second uplift of that portion of the ground had taken place between the time of the Limestone and that of the Upper Coal-measures. Moreover, as the Coal-measures were laid down at or below the sea-level, a third uplift has subsequently occurred whereby they were raised into dry land. By this simple and obvious kind of evidence, the relative ages of different mountain chains may be compared. In most great mountain chains, however, the rocks have been so intensely crumpled, and even inverted, that much labour may be required before their true relations can be determined.

The Alps offer an instructive example of a great mountain system formed by repeated movements during a long succession of geological periods. The central portions of the chain consist of gneiss, schists, granite, and other crystalline rocks, partly referable to the pre-Cambrian series, but some of which are metamorphosed Palæozoic, Secondary, and even older Tertiary deposits (p. 622). It would appear that the first outlines of the Alps were traced out even in pre-Cambrian times, and that after submergence, and the deposit of Palæozoic formations along their flanks, if not over most of their site, they were re-elevated into land. From the relations of the Mesozoic rocks to each other, we may infer that several renewed uplifts, after successive denudations, took place before the beginning of Tertiary times; but without any general and extensive plication. A large part of the range was certainly submerged during the Eocene period under the waters of that wide sea which spread across the centre of the Old World, and in which the nummulitic limestone and flysch were deposited. But after that period the grand upheaval took place to which the present magnitude of the mountains is chiefly due. The older Tertiary rocks, previously horizontal under the sea, were raised up into mountain-ridges more than 11,000 feet above the sea-level, and, together with the older formations of the chain, were crumpled, dislocated, and inverted. So intense was the compression and shearing to which clays and sands were subjected, that they were converted into hard crystalline rocks. It is strange to reflect that the enduring materials out of which so many of the mountains, cliffs, and pinnacles of the Alps have been formed are of no higher geological antiquity than the London Clay and other soft Eocene deposits of the south of England and the north of France and Belgium. At a later stage of Tertiary time, renewed disturbance led to the destruction of the lakes in which the molasse had accumulated, and their thick sediments were thrust up into large broken mountain masses, such as the Rigi, Rossberg, and other prominent heights along the northern flank of the Alps. Since that great movement, no paroxysm seems to have affected the Alpine region except the earthquakes, which from time to time show the process of mountain-making to be only suspended or still slowly in progress.

The gradual evolution of a continent during a long succession of geological periods has been admirably worked out for Europe by Suess and Neumayr, and for North America by Dana, Dawson, Dutton, Gilbert, Hayden, King, Newberry, Powell, and others. The general character of the structure of the American continent is extreme simplicity, as compared with that of the Old World. In the Rocky Mountain region, for example, while the Palæozoic formations lie unconformably upon pre-Cambrian gneiss, there is, according to King, a regular conformable sequence from the lowest Palæozoic to the Jurassic rocks. During the enormous interval of time represented by these massive formations, what is now the axis of the continent remained undisturbed save by a gentle and protracted subsidence. In the great depression thus produced, all the Palæozoic and a great part of the Mesozoic rocks were accumulated. At the close of the Jurassic period, the first great upheavals took place. Two lofty ranges of mountains—the Sierra Nevada (now with summits more than 14,000 feet high) and the Wahsatch—400 miles apart, were pushed up from the great subsiding area. These movements were followed by a prolonged subsidence, during which Cretaceous sediments accumulated over the Rocky Mountain region to a depth of 9000 feet or more. Then came another vast uplift, whereby the Cretaceous sediments were elevated into the crests of the mountains, and a parallel coast-range was formed fronting the Pacific. Intense metamorphism of the Cretaceous rocks is stated to have taken place. The Rocky Mountains, with the elevated table-land from which they rise, now permanently raised above the sea, were gradually elevated to their present height. Vast lakes existed among them, in which, as in the Tertiary basins of the Alps, enormous masses of sediment accumulated. The slopes of the land were clothed with an abundant vegetation, in which we may trace the ancestors of many of the living trees of North America. One of the most striking features in the later phases of this history was the outpouring of great floods of trachyte, basalt, and other lavas from many points and fissures over a vast space of the Rocky Mountains and the tracts lying to the west. In the Snake River region alone the basalts have a depth of 700 to 1000 feet, over an area 300 miles in breadth.

These examples show that the elevation of mountains, like that of continents, has been occasional, and perhaps sometimes paroxysmal. Long intervals elapsed, when a slow subsidence took place, but at last a point was reached when the descending crust, unable any longer to withstand the accumulated lateral pressure, was forced to find relief by rising into mountain ridges. With this effort the elevatory movements ceased. They were followed either by a stationary period, or more usually by a renewal of the gradual depression, until eventually relief was again obtained by upheaval, sometimes along new lines, but often on those which had previously been used. The intricate crumpling and gigantic inversions of a great mountain-chain naturally suggest that the movements which caused these disturbances of the strata were sudden and violent. And this inference may often, if not generally, be correct. It is not so easy, however, to demonstrate that a disturbance was rapid as to prove that it must have been slow. That some uplifts resulting in the rise of important mountain ranges have been almost insensibly brought about, can be shown from the operation of rivers in the regions affected. Thus the rise of the Uinta Mountains has been so quiet, that the Green River, which flowed across the site of the range, has not been deflected, but has actually been able to deepen its cañon as fast as the mountains have been pushed upward.[1] The Pliocene accumulations along the southern flanks of the Himalayas show that the rivers still run in the same lines as they occupied before the last gigantic upheaval of the chain (p. 1021).[1] A similar conclusion has been drawn from the river-valleys in the Elburz Mountains, Persia.[2]

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[1] Powell's "Geology of the Uinta Mountains," in the Reports of *U.S. Geographical and Geological Survey, Rocky Mountain Region*, 1876. The same conclusion is drawn by Gilbert from the structure of the Wahsatch Mountains. See his admirable essay on "Land

2. **Terrestrial Features due to Volcanic Action.**—The two types of volcanic eruptions described in Book III. Part I. give rise to two very distinct types of scenery. The ordinary volcanic vent leads to the piling up of a conical mass of erupted materials round the orifice. In its simplest form, the cone is of small size, and has been formed by the discharges from a single funnel, like many of the tuff and cinder-cones of Auvergne, the Eifel, and the Bay of Naples. Every degree of divergence from this simplicity may be traced, however, till we reach a colossal mountain like Etna, wherein, though the conical form is still retained, eruptions have proceeded from so many lateral vents that the main cone is loaded with minor volcanic hills. Denudation as well as explosion comes into play; deep and wide valleys, worn down the slopes, serve as channels for successive floods of lava or of water and volcanic mud. On the other hand, the type of fissure-eruption in which the lava, instead of issuing from a central vent, has flowed out from minor vents along the lines of many parallel or connected fissures, leads to the formation of wide lava-plains composed of successive level sheets of lava. By subsequent denudation, these plains are trenched by valleys, and, along their margin, are cut into escarpments with isolated blocks or outliers. Thus they become great plateaux or table-lands like those of north-west Europe, the Deccan and Abyssinia (pp. 258, 592).

The forms assumed by volcanic masses of older Tertiary and still earlier geological date are in the main due not to their original contours, but to denudation. The rocks, being commonly harder than those among which they lie, stand out prominently, and often, in course of time and in virtue of their mode of weathering, assume a conical form, which, however, has obviously no relation to that of the original volcano. Eminences formed after the type of the Henry Mountains (p. 571) owe their dome-shape to the subterranean effusion of erupted lava, but the superficial irregularities of contour in the domes must be ascribed to denudation.

3. **Terrestrial Features due to Denudation.**—The general results of denudation have been discussed in Book III. Part II. Sect. ii. Every portion of the land, as soon as it rises above the sea-level, is attacked by denuding agents. Hence the older a terrestrial surface, the more may it be expected to show the results of the operation of these agents. We have already seen how comparatively rapid are the processes of subaerial waste (p. 465). It is accordingly evident that the present contours of the land cannot be expected to reveal any trace whatever of the early terrestrial surfaces of the globe. The most recent

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Sculpture," in his "Geology of the Henry Mountains," published in the same series of Reports, 1877.

[1] Medlicott and Blanford, 'Geology of India,' p. 570.

[2] E. Tietze, *Jahrb. Geol. Reichsanst.* xxviii. (1878) p. 581.

mountain chains and volcanoes may, indeed, retain more or less markedly their original superficial outlines; but these must be more and more effaced in proportion to their geological antiquity.

The fundamental law in the erosion of the terrestrial surfaces is that harder rocks resist decay more, while softer rocks resist it less. The former consequently are left projecting, while the latter are worn down. The terms "hard" and "soft" are used here in the sense of being less easily and more easily abraded, though every rock suffers in some measure. If, therefore, a perfectly level surface, composed of rocks exceedingly unequal in power of resistance, were to be raised above the sea, and to be exposed to the action of weathering, it would eventually be carved into a system of ridges and valleys. The eminences would be mainly determined by the position of the harder rocks, the depressions by the site of the softer. Every region of Mesozoic or Palæozoic rocks affords ample illustration of this result. The hills and prominent ridges are found to be where they are, not so much because they have there been more upheaved, but because they are composed of more durable materials, or because, by the disposition of the original drainage-lines, they have been less eroded than the valleys.

In this marvellous process of land-sculpture, we have to consider, on the one hand, the agents and combinations of agents which are at work, and on the other, the varying powers of resistance arising from declivity, composition, and structure of the materials on which these agents act. The forces or conditions required in denudation — air, aridity, rain, springs, frost, rivers, glaciers, the sea, plant and animal life—have been described in Book III. Part II. Every country and climate must obviously have its own combination of erosive activities. The decay of the surface in Egypt or Arizona arises from a different group of forces from that which can be seen in the west of Europe or in New England.

In tracing the sculpture of the land, we are soon led to perceive the powerful influence of the angle of slope of the ground upon the rate of erosion. This rate decreases as the angle lessens, till on level plains it reaches its minimum. Other things being equal, a steep mountain ridge will be more deeply eroded than one of the same elevation which rises gradually out of the plains. Hence the declivity of the ground, at its first elevation into land, must have had an important bearing upon the subsequent erosion of the slopes. It is important to observe that the depressions into which the first rain gathered on the surface of the newly upraised land would, in most cases, become the permanent lines of drainage. They would be continually deepened as the water coursed in them, so that, unless where subterranean disturbance came into play, or where the channels were obstructed by landslips, volcanic ejections, or otherwise, the streams would be unable to quit the channels they had once chosen. The permanence of drainage-lines is one of the most remarkable features in the geological history of the continents. The main valleys of a country are usually among the oldest parts of its topography. As they are widened and deepened, the ground between them may be left projecting into high ridges and even into prominent isolated hills.

A chief element in the progress of land-sculpture is **geological structure**—the character, arrangement, and composition of the rocks, and the manner in which each variety yields to the attacks of the denuding agents. Besides the general relations of the so-called hard rocks to resulting prominences, and of soft rocks to depressions, the broader geotectonic characters have had a dominant influence upon the evolution of terrestrial contours. As illustrations of this influence, reference may be made to the marked difference between the scenery of districts composed of stratified sedimentary rocks, and that of areas of massive eruptive rocks, such as granite. In the former case, bedding and joints

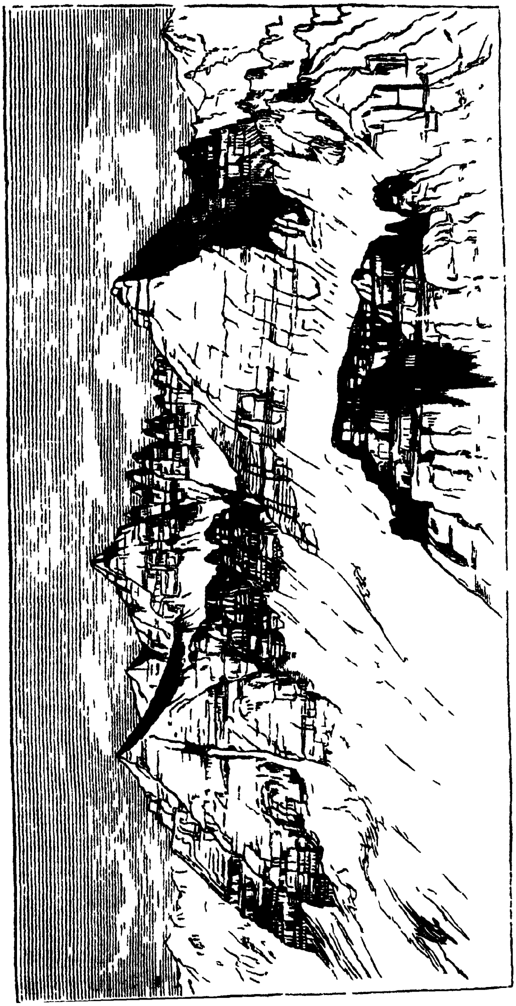

Fig. 400.—Outlines of Mountains formed of nearly horizontal Stratified Rocks, Rocky Mountains. (Hayden's 'Report of Survey of Western Territories,' 1874.)

furnish divisional lines, the guiding influence of which upon the external forms of the mountains is everywhere traceable. In the case of eruptive masses, the rock is split open along joints only, which mainly determine the shapes of crest, cliff, and corry.

Bedding produces a distinct type of scenery which can be traced from the sides of a mere brook up into tall sea-cliffs or into lofty mountain-groups. Moreover, much of the ultimate character of the scenery depends upon whether the strata have been left undisturbed; for the position of the bedding, whether flat, inclined, vertical, or contorted, largely determines the nature of the surface. The most characteristic scenery formed by stratified rocks is undoubtedly where the bedding is horizontal, or nearly so, and the strata are massive. A mountain constructed of such materials appears as a colossal pyramid, the level bars of stratification looking like gigantic courses of masonry. Joints and faults traversing the bedding allow it to be cleft into blocks and deep chasms that heighten the resemblance to ruined architecture. Probably the most marvellous illustrations of these results are to be found in the Western Territories of the United States. The vast table-lands of the River Colorado, in particular, offer a singularly impressive picture of the effects of mere subaerial erosion on undisturbed and nearly level strata (see Frontispiece). Systems of stream-courses and valleys, river gorges, unexampled elsewhere in the world for depth and length, vast winding lines of escarpment, like ranges of sea-cliffs, terraced slopes rising from plateau to plateau, huge buttresses and solitary stacks standing like islands out of the plains, great mountain masses towering into picturesque peaks and pinnacles, cleft by innumerable gullies, yet everywhere marked by the parallel bars of the horizontal strata out of which they have been carved — these are the orderly symmetrical characteristics of a country where the scenery is due entirely to the action of subaerial agents and the varying resistance of level or little disturbed stratified rocks.

On the other hand, where stratified rocks have been subjected to plications and fractures, their characteristic features may be gradually almost lost among those of the crystalline masses which under these circumstances are so often found to have been forced through them (see Fig. 252). The Alps may be cited as a well-known example of this kind of scenery. The whole geological aspect of these mountains is suggestive of former intense commotion. Yet on every side are to be seen proofs of the most enormous denudation. Twisted and crumpled, the solid sheets of limestone may be seen as it were to writhe from the base to the summit of a mountain, yet they present everywhere their truncated ends to the air, and from these ends it is easy to see that a vast amount of material has been worn away. Apart altogether from what may have been the shape of the ground immediately after the upheaval of the chain, there is evidence on every side of gigantic denudation. The subaerial forces that have been at work upon the Alpine surface ever since it first appeared have dug out the valleys, sometimes acting in original depressions, sometimes eroding hollows down the slopes. Moreover they have planed down the flexures, excavated lake-basins, scarped the mountain sides into cliff and *cirque*, notched and furrowed the ridges, splintered the crests into chasm and *aiguille*, until no part of the original surface now remains in sight. And thus the Alps remain a marvellous monument of stupendous earth-throes, followed by prolonged and gigantic denudation

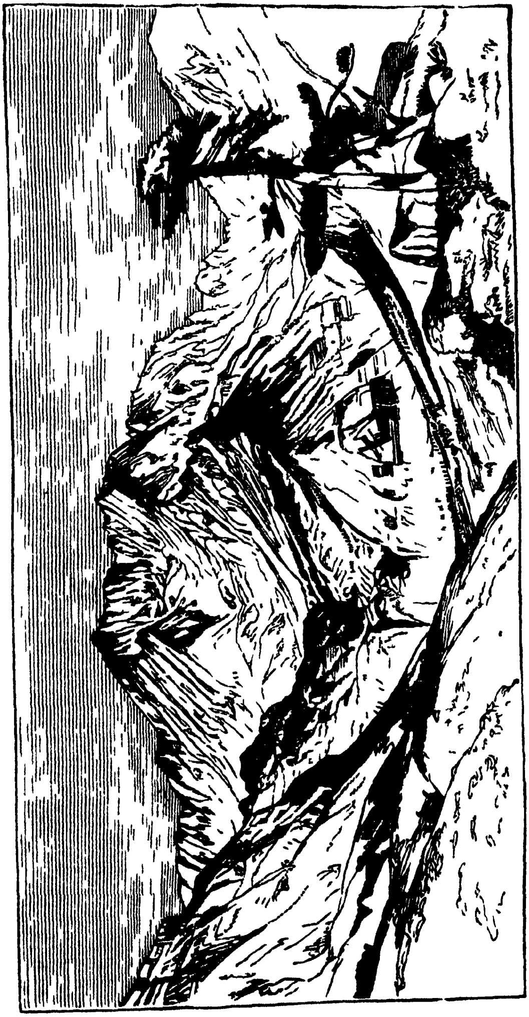

Fig 470 —Outlines of a Mountain formed of Massive Rocks Rocky Mountains (Hayden's 'Report of Survey of Western Territories, 1874)

In massive rocks, the structure lines are those of joints alone, and according to the direction of the intersecting joints the trend and shape of the ridges are determined. The importance of rock-joints, not only in details of scenery, but even in some of the main features of the mountain outlines of massive rocks, is hardly at first credible. It is along these

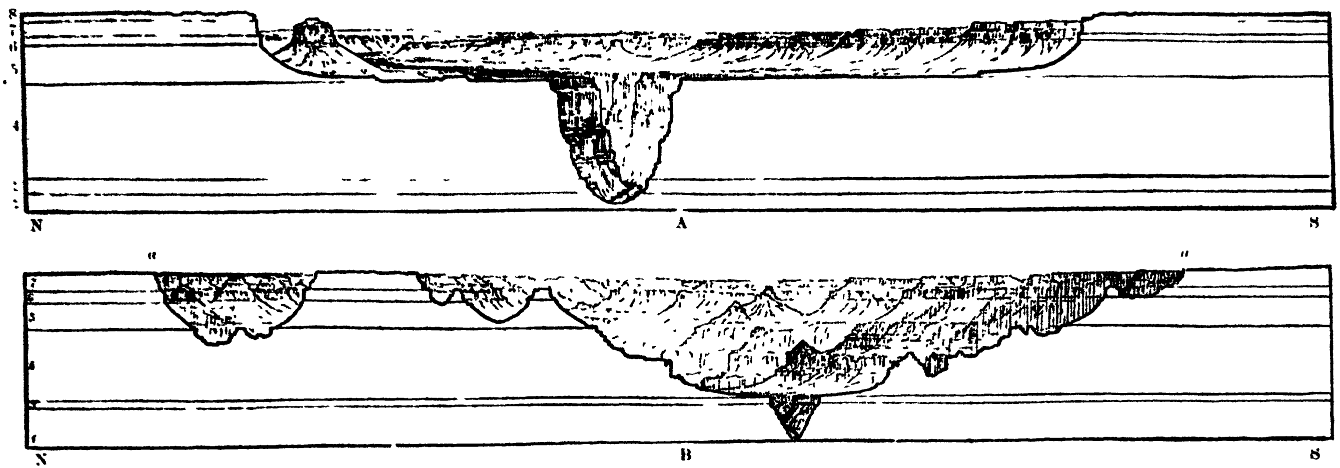

Fig. 471 —Sections across the Grand Cañon of the Colorado.[1]

(Vertical and Horizontal Scale the same)

A. Section in the Kanab division. B Section in the Kaibab division *a* to *a* seven miles.

		Thickness in A	Thickness in B.
Permo-Carboniferous	8. Bellerophon beds	250 ft	—
Coal-measures	7. Cherty Limestone	350 ,,	500 ft
	6 Cross-bedded Sandstone	200 .	400 ..
	5. Aubrey red Shales, &c	1200 ..	900 ,,
Lower Carboniferous	4. Red Wall	2500 ..	2200 .,
	3 Tonto group	300 ,,	200 ..
	2. Silurian rocks (covered unconformably by overlying rocks)	300 .	—
	1 Granite, Schist, &c , eroded before deposition of Carboniferous rocks	—	1200 ,,

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[1] Drawn on a true scale for this work by Mr. Holmes, whose diagrams of the geological structure and scenery of Western America are probably at once the most artistic and instructive sketches with which geological literature has yet been enriched. To his graphic pencil also the author owes the Frontispiece to this volume.

divisional lines that the rain has filtered, and the springs have risen, and the frost wedges have been driven. On the bare scarps of a high mountain, where the inner structure of the mass is laid open, the system of joints is seen to have determined the lines of crest, the vertical walls of cliff and precipice, the forms of buttress and recess, the position of cleft and chasm, the outline of spire and pinnacle. On the lower slopes, even under the tapestry of verdure which nature delights to hang where she can over her naked rocks, we may detect the same pervading influence of the joints upon the forms assumed by ravines and crags. Each kind of eruptive rock has its own system of joints, and these in large measure determine its characteristic type of scenery.

A few of the more important features of the land may be briefly noticed here in their relation to this branch of geology. In the physiography of any region, mountains are the dominant features (p. 40). A true mountain-chain consists of rocks that have been crumpled and pushed up in the manner already described. But ranges of hills, almost mountainous in their bulk, may be formed by the gradual erosion of valleys out of a mass of original high ground. In this way, some ancient table-lands have been so channelled that they now consist of massive rugged hills, either isolated or connected along the flanks. Eminences detached by erosion from the masses of rock whereof they once formed a part, have been termed *hills of circumdenudation*. Their isolation may either be due to the action of streams working round them, apart altogether from geological structure, or to their more resisting constitution, which has enabled them to remain prominent during the general degradation of the whole surface,

Table-lands (p. 43) may sometimes arise from the abrasion of hard rocks and the production of a level plain by the action of the sea, or rather of that action combined with the previous degradation of the land by subaerial waste (p. 470). Such a form of surface may be termed a *table-land of erosion*. Notable examples are to be seen in the extensive "fjelds" or elevated plateaux of Scandinavia, many of which, rising above the snow-line, form the gathering-ground of glaciers that descend almost to the sea-level. Fragments of a similar table-land may be recognised among the Grampian Mountains of Scotland. But most of the great table-lands of the globe seem to be platforms of little disturbed strata, either sedimentary or volcanic, which have been upraised bodily to a considerable elevation. These may be termed *table-lands of deposit*. But, whatsoever its mode of origin, the plateau undergoes a gradual transformation under continued denudation. No sooner are the rocks raised above the sea, than they are attacked by running water, and begin to be hollowed out into systems of valleys. As the valleys sink, the platforms between them grow into narrower and more definite ridges, until eventually the level table-land is converted into a complicated network of hills and valleys, wherein, nevertheless, the key to the whole arrangement is furnished by a knowledge of the disposition and effects of the flow of water. The examples of this process brought to light in Colorado, Wyoming, Nevada, and the other Western Territories, by Newberry, King, Hayden, Powell, Gilbert, Dutton, and other explorers, are among the most striking monuments of geological operations in the world. The erosion of the ancient table-lands of Scandinavia and Scotland, and their conversion into systems of hilly ridges and valleys, convey less impressive but still instructive evidence of the efficacy of subaerial waste.

Watersheds are of course at first determined by the form of the earliest terrestrial surface. But they are less permanent than the watercourses that diverge from them. Where a watershed lies symmetrically along the centre of a country or continent, with an equal declivity and rainfall on either side, and an identity of geological structure, it will be permanent, because the erosion on each slope proceeds at the same rate. But such a combination of circumstances can happen rarely, save on a small and local scale. As a rule, watersheds lie on one side of the centre of a country or continent, and the declivity is steeper on the side nearest the sea. Hence, apart from any influence from difference of geological structure, the tendency of erosion, by wearing the steep slope more than the gentle one, is to carry the watershed backward nearer to the true centre of the region, especially at the heads of valleys. Of course this is an extremely slow process; but it must be admitted to be one of real efficacy in the vast periods during which denudation has continued. Excellent illustrations of its progress, as well as of many other features of land-sculpture, may often be instructively studied on clay-banks exposed to the influence of rain.[1]

The crests of mountains are watersheds of the sharpest type, where erosion has worked backward upon a steep slope on either side. Their forms are mainly dependent upon structure, and especially upon systems of joints. It will often be observed that the general trend of a crest coincides with that of one set of joints, and that the bastions, recesses, and peaks have been determined by the intersection of another set. If the rock is uniform in structure, and the declivity equal in angle on either side, a crest may retain its position; but as one side is usually considerably steeper than the other, the crest advances at the expense of the top of the gentler declivity. But, under any circumstances, it is continually lowered in level, for it may be regarded as the part of a mountain where the rate of subaerial denudation reaches a maximum. An ordinary cliff is attacked only in front, but a crest has two fronts, and is further splintered along its summit. Nowhere can the guiding influence of geological structure be more conspicuously seen than in the array of spires, buttresses, gullies, and other striking outlines which a mountain crest assumes.

Valleys are mainly due to erosion, guided either by original depressions of the ground, or by geological structure, or by both.[2] Their contours depend partly on the structure and composition of the rocks, and partly on the relative potency of the different denuding agents. Where the influence of air, rain, frost and general subaerial weathering has been slight, and the streams, supplied from distant sources, have had sufficient declivity, deep, narrow, precipitous ravines or gorges have been excavated. The cañons of the Colorado are a magnificent example of this result (Fig. 471). Where, on the other hand, ordinary atmospheric action has been more rapid, the sides of the river channels have been attacked, and open sloping glens and valleys have been hollowed out. A gorge or defile is usually due to the action of a waterfall, which, beginning with some abrupt declivity or precipice in the course of the river when it first commenced to flow, or caused by some hard rock crossing the channel, has eaten its way backward, as already explained (p. 388).

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[1] See on this subject Mr. Gilbert's suggestive remarks in the Essay on 'Land Sculpture' already cited (p. 984). See also *Nature*, xxix. (1884) p. 325, where the history of the watersheds of the British Isles is traced.

[2] The student should read the suggestive essay by the late J. B. Jukes (*Quart. Journ.*

A pass is a portion of a watershed which has been cut down by the erosion of two valleys, the heads of which adjoin on opposite sides of a ridge. Each valley is cut backward until the intervening ridge is demolished. Most passes no doubt lie in original but subsequently deepened depressions between adjoining mountains. The continued degradation of a crest may obviously give rise to a pass.

Lakes may have been formed in several ways. 1. By subterranean movements, as, for example, in mountain-making and in volcanic explosions. The subsidence of the central part of a mountain system might conceivably depress the heads of the valleys below the level of portions farther from the sources of the stream. Or the elevation of the lower parts of the valleys might cause an accumulation of water in their upper parts. Or each lake-basin might be supposed to be due to a special subsidence. But these hollows, unless continually deepened by subsequent movements of a similar nature, would be filled up by the sediment continually washed into them from the adjoining slopes. The numerous lakes in such a mountain system as the Alps cannot be due merely to subterranean movements, unless we suppose the upheaval of the mountains to have been quite recent, or that subsidence must take place continuously or periodically below each independent basin. But there is evidence that the Alpine uplift is not of such recent date, while the idea of perpetuating lakes by continued local subsidence would demand, not in the Alps merely, but all over the northern hemisphere, where lakes are so abundant, an amount of subterranean movement of which, if it really existed, there would assuredly be plenty of other evidence. 2. By irregularities in the deposition of superficial accumulations prior to the elevation of the land, or, in the northern parts of Europe and America, during the disappearance of the ice-sheet. The numerous tarns and lakes enclosed within mounds and ridges of drift-clay and gravel are examples. 3. By the accumulation of a barrier across the channel of

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Geol. Soc. xviii. (1862) p. 378, which was the first attempt to work out the history of the excavation of a valley system in reference to the geological history of the ground. See also Penck, *Neues Jahrb.* 1890, p. 165; E. Tietze, *Jahrb. Geol. Reichsanst.* xxxviii. (1888) p. 633.

a stream and the consequent ponding back of the water. This may be done, for instance, by a landslip, by a lava-stream, by the advance of a glacier across a valley, or by the throwing up of a bank by the sea across the mouth of a river. 4. *By* erosion. Water keeping stones in gyration can dig out pot-holes in the bed of a river, or on the sea-shore. Unequal subaerial weathering may cause rocks to rot much more deeply in some places than in others, so that, on the removal of the rotted material, the surface of the solid rock might be full of depressions. But the only known agent capable of excavating such hollows as might form rock-basin lakes is glacier-ice (p. 427). It is a remarkable fact, of which the significance may now be seen, that the innumerable lake-basins of the northern hemisphere lie on surfaces of intensely ice-worn rock. The striæ can be seen on the smoothed rock-surfaces slipping into the water on all sides. These striæ were produced by ice moving over the rock. If the ice could, as the striæ prove, descend into the rock-basins and mount up the farther side, smoothing and striating the rock as it went, it could, to a certain depth at least, erode basins.

In the general subaerial denudation of a country, innumerable minor features are worked out as the structure of the rocks controls the operations of the eroding agents. Thus, among undisturbed or gently inclined strata, a hard bed resting upon others of a softer kind is apt to form along its outcrop a line of cliff or escarpment. Though a long range of such cliffs resembles a coast that has been worn by the sea, it may be entirely due to mere atmospheric waste. Again, the more resisting portions of a rock may be seen projecting as crags or knolls. An igneous mass will stand out as a bold hill from amidst the more decomposable strata through which it has risen. These features, often so marked on the lower grounds, attain their most conspicuous development among the higher and barer parts of the mountains, where subaerial disintegration is most rapid. The torrents tear out deep gullies from the sides of the declivities. Corries or cirques, if not originally scooped out by converging streamlets (their mode of formation is a somewhat difficult problem), are at least enlarged by this action, and their naked precipices are kept bare and steep by the wedging off of successive slices of rock along lines of joint. Harder bands of rock project as massive ribs down the slopes, shoot up into prominent peaks, or, with the combined influence of joints and faults, give to the summits the notched saw-like outlines they so often present.

The materials worn from the surface of the higher are spread out over the lower grounds. We have already traced how streams at once begin to drop their freight of sediment when, by the lessening of their declivity, their carrying power is diminished (p. 393). The great plains of the earth's surface are due to this deposit of gravel, sand, and loam. They are thus monuments at once of the destructive and reproductive processes which have been in progress unceasingly since the first land rose above the sea and the first shower of rain fell. Every pebble and particle of the soil of the plains, once a portion of the distant mountains, has travelled slowly and fitfully downward. Again and again have these materials been shifted, ever moving seaward. For centuries, perhaps, they have taken their share in the fertility of the plains and have ministered to the nurture of flower and tree, of the bird of the air, the beast of the field, and of man himself. But their destiny is still the great ocean. In that bourne alone can they find undisturbed repose, and there, slowly accumulating in massive beds, they will remain until, in the course of ages, renewed upheaval shall raise them into future land, and thereby enable them once more to pass through a similar cycle of change.

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